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FORECASTING PRECIPITATION ON THE WEST SLOPE OF COLORADO

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ABSTRACT

The problem of forecasting precipitation on the west slope of Colorado is discussed. Synoptic situations which result in precipitation on the west slope of Colorado are described. These lead to the selection of five map types upon which an objective aid for forecasting is based. A number of variables are explored under each type and are combined by graphical correlation techniques to arrive at final forecasting charts. The results and test are summarized in the form of skill scores above chance and percent correct forecasts.

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INTRODUCTION

The purpose of this study is to set up objective procedures for forecasting rainfall in western Colorado. In developing the procedures, considerable time was spent in exploratory efforts to find relations between the factual information available at forecast time, and subsequent weather. The methods of attack follow in general those used in similar studies by Brier [1], Vernon [2], Penn [3], and others. The principal sources of ideas for the selection of variables to be tested and for typing situations were the forecasting staff at the Denver Forecast Center and previous research papers, including those by Reed [4], Carpenter [5], and Laird [6].

The forecast area covered in this study includes all of the stations from the north to south borders of Colorado west of the Continental Divide for which sufficient records were available from the surface and other charts. Reporting stations selected from this area were Craig, Eagle, Grand Junction, and Durango. Craig is in northwestern Colorado, Grand Junction and Eagle are in the west central, and Durango is located in the southwestern part of the state. A study of the terrain shows that the exposures of the four stations are quite dissimilar; Durango at an elevation of 6,800 feet has a southern exposure, Grand Junction at 4,800 feet and Craig at 6,300 feet are situated with their lowest terrain to the west-northwest, while Eagle at 6,500 feet is a typical mountain station. The variation in altitude of 2,000 feet is not too great, for some of the mountain passes in the forecast area go to nearly 12,000 feet.

For purposes of verification some definite distinction between a precipitation day and a no-precipitation day was necessary. Because so many areas on the west slope are higher than the reporting stations and are therefore likely to get more precipitation than the stations themselves, it was decided that a trace at any one station should define a precipitation day.

The spring months only, March, April, and May, were used in this investigation for two reasons. First, the synoptic conditions are more or less similar during this period of rapidly moving systems, and are quite dissimilar to the summer or mid-winter conditions. Second, the spring months produce more weather than the other seasons as well as more frequent and rapid changes in weather.

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Data from the springs of 1947 and 1948 were used to develop the original graphs and data from the spring of 1949 were used as independent or test data. The time for all surface data is 2330 MST and for all upper air data 2030 MST. The forecast period is the twelve hours from 0530 MST to 1730 MST of the following day.

PRECIPITATION TYPES

As a background for much of the discussion to follow, a brief description is now given of the important synoptic types that produce precipitation on the west slope of Colorado. As has been pointed out by forecasters of the Rocky Mountain Region, west slope and east slope weather problems are different, chiefly in that a marked change in the wind to bring about upslope flow is nearly always necessary for significant precipitation to occur along the east slope, while on the west side of the mountains, the normal flow of the air is upslope. In an earlier paper, the writer [6] studied weather charts from 1943 through 1947 for all of the twelve months, and from a detailed analysis of poor weather conditions (fair weather types were passed over rather briefly), found that the following four fairly specific synoptic types produce most of the precipitation on the west slope:

1. The Pacific front, southerly type, usually moves into Colorado through Southern California and Arizona. It may or may not produce general precipitation to the west of Colorado. It is accompanied by a surface low pressure system and, in general, an upper trough. Cold air advection may be weak to strong; the relative humidity is nearly always high at upper levels. The rate of movement and consequently the duration of the storm is closely related to whether there is an open trough or a closed Low aloft. This type almost always produces precipitation over western Colorado, and the problem becomes one of timing.

2. The Pacific front, northerly type, moves inland across the northern or middle Pacific coast to Idaho, Nevada, and Utah. The characteristics of this type are similar to those of the southerly type, except that the changes are farther north, and western Colorado may receive only the weak southern tip of this front. The direction of wind flow aloft may change only 20° to 40° in the upper trough with one of these fronts, and therefore moisture content becomes a critical factor as to whether the west slope valleys will receive even a trace of precipitation. The two Pacific types were combined in the present study because of the wide range of areas affected by each one and because of similar characteristics.

3. The upper level anticyclone centered over the lower Mississippi Valley is associated with some of the heaviest downpours, together with numerous thunderstorms, throughout the mountain and intermountain region. To receive the greatest amount of rainfall western Colorado should be in southerly or southwesterly wind flow along the back side of the high cell. This normally is a late summer or fall occurrence and therefore does not apply as a definite type in this study.

4. The continental polar front which moves southward out of Canada may or may not produce precipitation on the west slope depending upon several factors. Many of these fronts move down along the east slope of the mountains and out eastward producing no precipitation at all west of the Continental Divide. If the top of the cold air is at least 10,000 feet above sea level, and particularly when a surface low center or deep trough has developed over or near Nevada, all of the western valleys may get moderate rain or snow.

PRELIMINARY STUDY

Since in this study all of the maps had to be considered instead of just the rain type, some variable which could be evaluated regardless of frontal systems had to be used as a starting point. It was found that the most predominant feature of a rain type was the low pressure system over the Plateau, while the most prominent feature of the dry type was the high pressure over the same area. Therefore the difference in sea level pressure between San Francisco and Milford, Utah was one of the first variables investigated. This algebraic difference gives a good indication of a High or Low over the Plateau approaching Colorado but not yet upon it.

Because previous studies, such as those mentioned in the introduction, and the experiences of the Denver staff had suggested that moisture in the upper levels is also a critical element, a preliminary analysis was made of the radiosonde observations from Boise, Ely, Medford, Phoenix, Las Vegas, and Lander. This analysis showed the moisture at Ely to have the highest correlation with precipitation in western Colorado during the forecast period, if no other factors were considered.

A preliminary study was then completed using all of the maps for March, April, and May 1947 and 1948. With the two variables, (1) relative humidity at 700 mb. at Ely, and (2) sea level pressure difference, San Francisco minus Milford, a scatter diagram was plotted and the "dry" side of the graph separated from the "wet" side with a curved line. From this separation an accuracy of about three out of four was obtained. On check data the accuracy was a little less. A study of the failures in this procedure showed, as was expected, that a good many other factors should be considered. After these failures were analyzed, a typing procedure together with additional variables which became apparent, was decided upon as the best approach.

MAP TYPES AND VARIABLES

Four definite map types related to the precipitation types already discussed and a fifth so-called "indefinite" type were set up. These classifications were: (1) The

700-mb. Low type, (2) the MP front type, (3) the CP front type, (4) the MP and CP double front type, and (5) the indefinite type. These types are defined and described in detail below. The 700-mb. Low type needs some explanation since it often accompanies one of the frontal types. After the front passes to the east or south of the forecast area, the variables used for frontal types can no longer be used. Also whether or not precipitation continues over western Colorado during the following forecast period depends a great deal on whether or not an upper Low has developed and its position with respect to the Continental Divide.

The following variables were investigated for these five types; considerable time and effort went into testing their usefulness, and those which proved to be significant were included in the final procedures:

1. Sea level pressure difference, San Francisco minus Milford. (Used for types 1, 2, 3, and 5.)
2. 700-mb. relative humidity at Grand Junction. (Used for type 2.)
3. Average 700-mb. relative humidity upstream. (Used for types 2, 3, and 4.)
4. Position of the 700-mb. low center. (Used for type 1.)
5. Average mixing ratio at Grand Junction, surface to 700 mb. (Not used.)
6. 700-mb. wind direction at Grand Junction. (Used for type 5.)
7. 700-mb. relative humidity at Ely. (Used for for type 5.)
8. Surface dew points at the verification stations. (Not used.)
9. Surface dew point spread at the verification stations. (Not used.)
10. Milford sea level pressure. (Not used.)
11. Sea level pressure difference, Billings minus Grand Junction. (Used for type 4.)

INVESTIGATIONS BY TYPE

TYPE 1. 700-MB. LOW

Type 1 included all cases where the 700-mb. chart showed the center of a closed Low to be over Colorado, Utah, Arizona, New Mexico, or those portions of Nevada and California east of a line connecting the northwest corner of Utah and Point Conception on the California coast. (See fig. 1.)

A forecast of precipitation on the basis of the existence of such a Low alone would yield a high forecast accuracy. There were 18 Lows in this area during the 6 months of dependent data, 15 of which produced precipitation at at least one of the four verification stations. Further study of the position of the center of the Low with respect to the Continental Divide, in conjunction with the indications of the sea level pressure difference between San Francisco and Milford gave even better results. If the center of the Low is east of the Divide and the sea level pressure difference is negative, indicating high pressure building up or approaching western Colorado, the likelihood of precipitation is less than if the low center is west of the Divide. These results are given in table 1. These results are tentative and must remain so until enough additional cases of the same type have been accumulated to verify them. Although there were eleven Lows in the three test months of 1949, and all produced precipitation, all were west of the Divide.

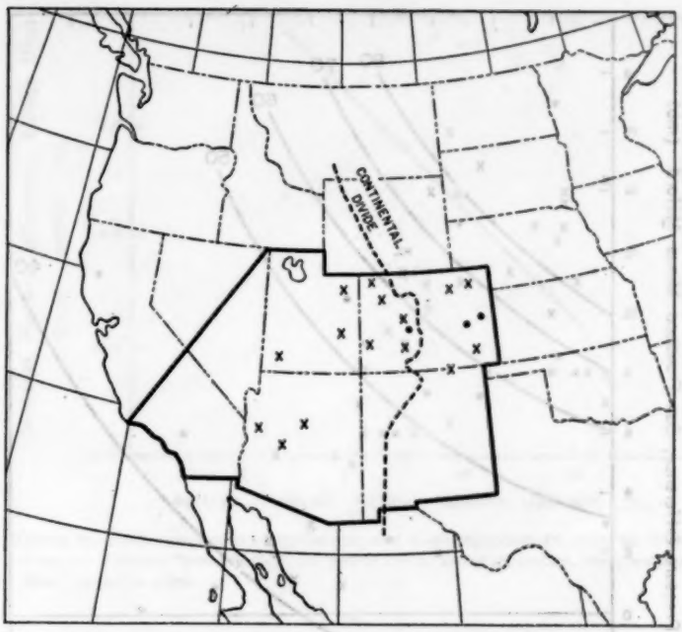

FIGURE 1.—Map showing area (heavy outline) in which center of Low at 700 mb. must be located for case to be classified as Type 1. Cross indicates location of Low in cases followed by precipitation during forecast period, and dot, no-precipitation.

TABLE 1.—*Ratio of number of precipitation cases (numerator) to total number of cases (denominator) for joint categories of sea level pressure difference between San Francisco (SFO) and Milford (MLF), and of the position of the 700-mb. Low relative to the Continental Divide.*

Type 1. 700-mb. Low		Position of the 700-mb. Low relative to the Continental Divide	
		West	East
Sea Level Pressure Difference, SFO−MLF	>0	$\frac{10}{11}$	$\frac{3}{3}$
	<0	$\frac{1}{1}$	$\frac{1}{3}$

TYPE 2. MP FRONTS

Type 2 included all maps with a Pacific front within the continental United States and west of Colorado on the 2330 MST map. A little difficulty was encountered on a very few maps because once in a while a very weak front was carried on the map when characteristics were so weak as to be negligible. Also there were a few instances where fronts carried at 2330 MST were dropped at the

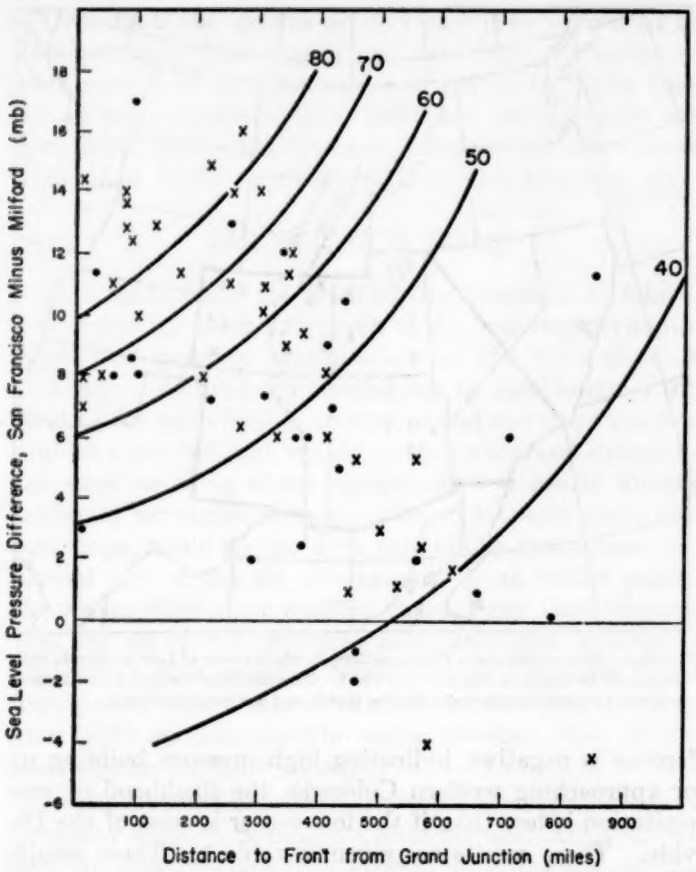

FIGURE 2.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 2 maps. Isopleths are drawn for percent frequency ("probability") or precipitation occurrence.

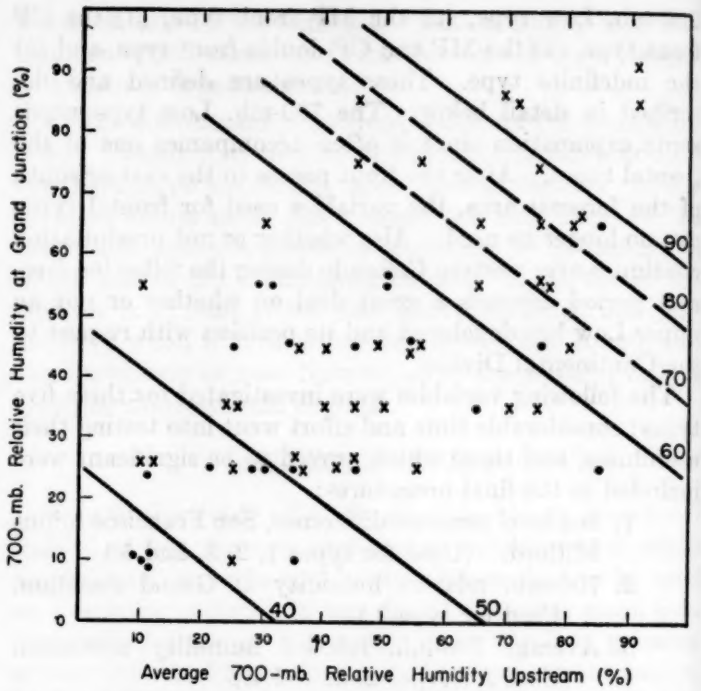

FIGURE 3.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 2 maps. Isopleths are drawn for percent frequency ("probability") of precipitation occurrence.

following period. However, to have a specific criterion for defining type 2 it was decided to retain the original definition which was fulfilled by any MP front at 2330 MST.

The following are the final variables selected for this type: (1) Sea level pressure difference, San Francisco minus Milford, (2) distance, in miles, to the front from Grand Junction, (3) 700-mb. relative humidity at Grand Junction, and (4) average 700-mb. relative humidity upstream from western Colorado. The upstream relative humidity was found as follows: Two contour lines were drawn upstream from the northwest and southwest corners of Colorado parallel to the contour lines of the 700-mb. chart. If the average wind velocity was less than thirty knots the inner circle of raobs within the contour channel was considered, including Ogden, Ely, Las Vegas, Phoenix, and Albuquerque. If the speed was greater than thirty knots, Boise, Oakland, and Santa Maria were also considered.

The variables were combined by graphical correlation techniques which have been adequately explained in a number of recent papers [1, 2, 3] and need not be described in detail here. The variables were combined according to the following diagram:

Sea level pressure difference, San Francisco minus Milford	Probability from figure 2	Forecast from figure 4
Distance to front from Grand Junction		
700-mb. relative humidity at Grand Junction	Probability from figure 3	
Average 700-mb. relative humidity upstream		

Only a "forecasting" line, or line of best separation of precipitation from no-precipitation, is drawn in figure 4. A forecast of precipitation is made if the point falls above the line and no-precipitation if the point falls below the line.

TYPE 3. CP FRONTS

Type 3 included all maps with a continental front moving southward through Montana or Wyoming. Stationary fronts were not included in this category.

The variables selected for this type are: (1) Sea level pressure difference, San Francisco minus Milford, and (2) average 700-mb. relative humidity upstream. The variables were combined in a scatter diagram, figure 5. That the line of separation on this chart is almost horizontal indicates that the pressure difference is adding but little to the results obtainable from the relative humidity alone. Moreover, none of the other variables investigated under this type added materially to the results obtained from the average relative humidity upstream.

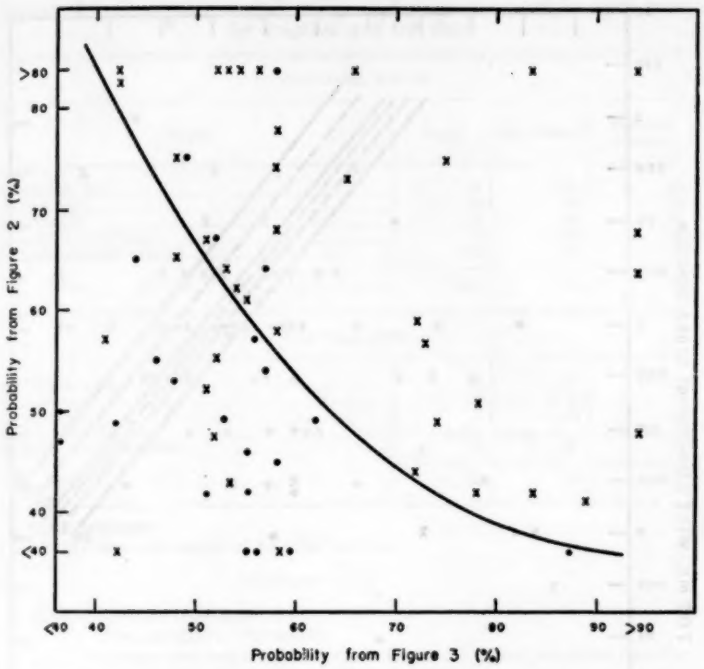

FIGURE 4.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 2 maps plotted as a function of probabilities from figures 2 and 3. Forecast "precipitation" for points above line of separation, "no-precipitation" for points below.

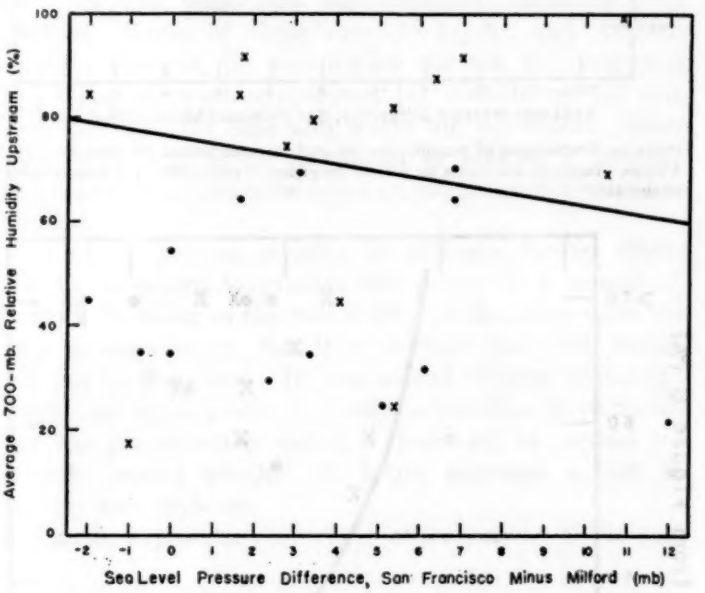

FIGURE 5.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 3 maps. Forecast "precipitation" for points above line of separation, "no-precipitation" for points below.

TYPE 4. MP PLUS CP FRONTS

Type 4 included all maps on which both MP and CP types of fronts as described under types 2 and 3 exist at the same time. Stationary fronts which stagnate along the east slope of the mountains of Colorado and Wyoming are not included here.

The variables selected in this type are: (1) Sea level pressure difference, Billings minus Grand Junction, and

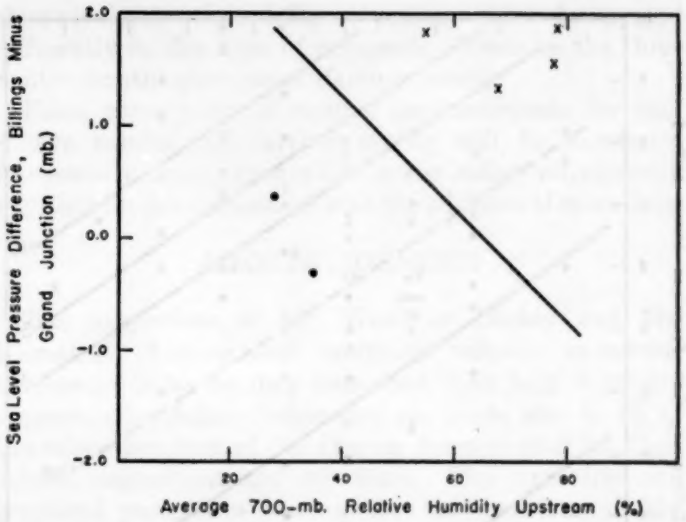

FIGURE 6.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 4 maps. Forecast "precipitation" for points above line of separation, "no-precipitation" for points below.

(2) average 700-mb. relative humidity upstream. The scatter diagram combining these two variables is shown in figure 6. While a very good separation of the cases is evident, the few cases of this type makes the position of the line of separation rather indefinite. Until more cases are included only an approximation of the best position of the line is possible.

TYPE 5. INDEFINITE

Type 5 included all maps not belonging to one of the other types. This "indefinite" type was the most frequent single type and was the most difficult to handle. The dry type or Plateau High usually fell into this classification. The indifferent type or so-called flat pressure map often was placed in this category. No definite fronts were present, but often considerable upper level moisture and a westerly wind flow brought into play the orographic effects.

The final variables selected under this type were: (1) Sea level pressure difference, San Francisco minus Milford, (2) 700-mb. relative humidity at Ely, and (3) the 10,000-foot, or 700-mb., wind direction at Grand Junction. These were combined as follows:

Sea level pressure difference, San Francisco minus Milford	Probability from figure 7	Forecast from figure 9
700-mb. relative humidity at Ely		
Sea level pressure difference, San Francisco minus Milford	Probability from figure 8	
700-mb. wind direction at Grand Junction		

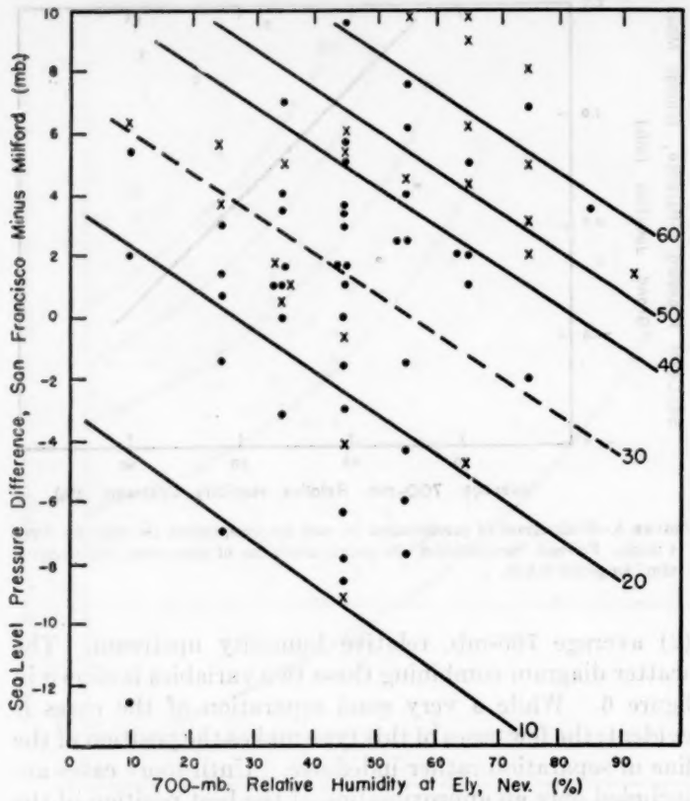

FIGURE 7.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 5 maps. Isopleths are drawn for percent frequency ("probability") of precipitation occurrence.

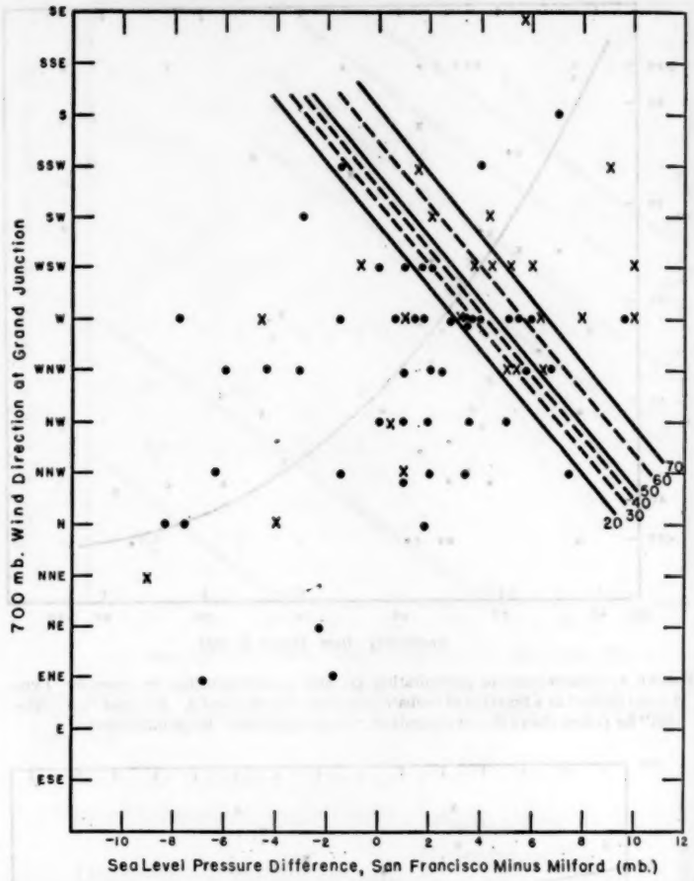

FIGURE 8.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 5 maps. Isopleths are drawn for percent frequency ("probability") of precipitation occurrence.

A line of separation was drawn on this chart, with rain cases predominately above the line and non-rain cases below the line.

RESULTS

A total of 275 maps were analyzed, including both original and test data. The results are summarized by types in table 2.

No attempt was made to compare these results directly with official Weather Bureau forecasts since a strict verification of the official forecasts is virtually impossible. That is, a forecast of showers over the higher mountains, southwestern, or northwestern mountains is often correct even though none falls at any of the valley stations, and district forecasts for the specific stations are not made.

CONCLUSIONS

The results point out several facts of importance. First, the 700-mb. Low type produced a high skill score and percentage correct, and the indefinite type gave in general the least satisfactory results. This was to be expected since the first type is obviously a precipitation type while the last type includes all maps not of definite characteristics. However, it means that more refinement should be attempted in this last type, particularly since it is the most frequent category.

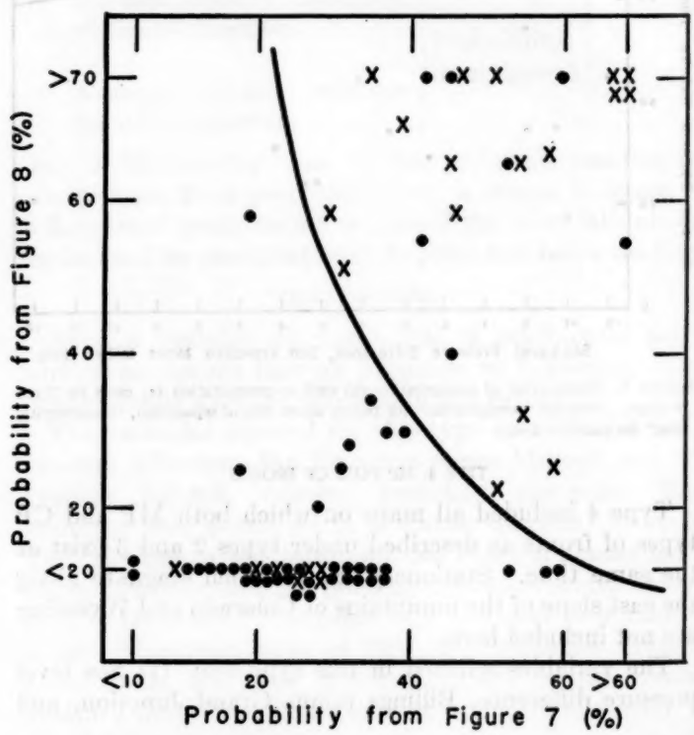

FIGURE 9.—Scattergram of precipitation (x) and no-precipitation (•) cases for Type 5 maps plotted as a function of probabilities from figures 7 and 8. Forecast "precipitation" for points above line of separation, "no-precipitation" for points below.

TABLE 2.—*Summary of skill scores and percent correct for each type for original and test data*

Type	Cases	Skill Score*	Percent correct
Original Data, 1947–48			
1. 700-mb. Low	18	0.60	89
2. MP front	62	.63	82
3. CP front	26	.62	81
4. MP plus CP front	6	1.00	100
5. Indefinite (all others)	72	.56	81
Total	184	.65	83
Test Data, 1949			
1. 700-mb. Low	11	(1)	100
2. MP front	40	0.21	63
3. CP front	7	.33	71
4. MP plus CP front	none		
5. Indefinite (all others)	33	.29	64
Total	91	.36	67

[1] Indeterminate

* Skill scores were computed from the formula:

$$\text{Skill Score} = \frac{C - E_e}{T - E_e}$$

Where: C = observed number of correct forecasts.
T = total number of forecasts.
E_e = expected number of correct forecasts due to chance, computed from the marginal totals of the contingency table.

Second, in the interest of keeping the study in a simple form, several important meteorological elements were omitted. Some of these are: (1) 3-, 6-, and 12-hour pressure changes, (2) stability of the air, (3) deepening and filling of pressure systems, (4) subsidence, (5) convergence, and (6) cold and warm air advection. Since all of these should be considered in making a forecast, this study should be considered an aid and not a complete method.

Third, the forecast period is for 12 hours; further efforts will be necessary to expand this period to a second 12 hours. In doing so the use of some of the same variables may be satisfactory, but it is obvious that their values will not be the same. By the second 12-hour period the conditions which produced precipitation often have passed and the precipitation ended. Therefore, to expand the forecast period another 12 hours becomes almost an entirely new problem.

Fourth, exploratory efforts in other seasons of the year showed clearly that different seasons must be treated differently in this type of approach. Tests on the three winter months gave unsatisfactory results.

Fifth, three years of records are inadequate for conclusive results and further testing will be necessary. Particularly those types which occur rather infrequently will need further refinement with the addition of more data.

ACKNOWLEDGMENTS

The suggestions of Mr. Woodrow Dickey and Mr. Forrest E. Horning were extremely valuable in solving various problems as they arose and their help is greatly appreciated. Acknowledgments are made also to all of the other members of the Denver forecast staff for their helpful suggestions and criticisms. The statistical and graphical procedures were under the direction of Mr. Dickey.

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HURRICANES OF THE 1950 SEASON

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GENERAL SUMMARY

The hurricane season of 1950 was an active one in the Atlantic. It gave 12 storms, 11 of which developed full hurricane force. Eleven is the largest number of full hurricanes reported for a season, in history. However, the record number of starts is 21, set in 1933; only 10 of these 21 storms developed into full hurricanes. One of the 11 hurricanes of 1950 developed hurricane force twice in its course with a wave stage between. In reality, it might be classed as two separate hurricanes that developed at different times from the same easterly wave, in which case the number of full hurricanes would be 12. Four of the storms entered the United States mainland and two others came close enough to give strong winds at Cape Hatteras or Cape Cod, but did not move inland. Property and crop damage in the United States was about $35,850,000 and 19 lives were lost. These numbers include damage of $2,000,000 and loss of 12 lives in New England coastal areas.

The first hurricane of the 1950 season was noted August 12. Before this, the tropical Atlantic had been remarkably quiet; not even an "easterly wave" worthy of note had appeared. The August 12 hurricane was the first of a family of six that scarcely gave a break until September 16. Much of the time during this period of 37 days, there were two or three hurricanes in progress at the same time. Beginning with September 17, there ensued 14 days without hurricane formation, but on October 1, the first of another family of six storms appeared. These gave but a few days respite until October 21, when the season ended. The 70-day period from August 12 to October 21 constituted the hurricane season of 1950. It began late and ended early, but while it lasted was packed with activity seldom, if ever, before observed.

From the forecasters' point of view and the experience of airplane reconnaissance crews, the season presented more exasperation and hard work to keep track of the storms than any other year of our experience. The track chart (fig. 1) shows many slow movements, blockings, changes in course, and even loops. In addition, increases and losses of intensity of a number of the storms over short periods of time presented unusual difficulties. For example, the hurricane of September 1 to 7 made two small loops in the northeastern Gulf area and another 180° turn over Florida which gave four abrupt changes in course in 3 days [1]. The late October hurricane in the Gulf added rapid deepening and filling to an erratic course, and caused subsequently needless warnings and public anxiety on the Florida West Coast. During the last 12 hours as it approached the coast, it lost force rapidly from a hurricane of 100 m. p. h. to a storm of only moderate gale force as it moved inland in the Cedar Keys-Cross City area.

Another unusual feature that may be noted from figure 1 is the number of times two or more hurricanes were in progress simultaneously. During the period August 27 to 31, two hurricanes were in progress in the Atlantic; and from September 2 to 6, three fully developed hurricanes were noted, two in the western Atlantic and one in the Caribbean-East Gulf area. From October 1 to 5, there was a hurricane in the Atlantic and a tropical storm in the western Gulf of Mexico; again, from October 14 to 16 and on October 18–19, two hurricanes were in progress at the same time. It is not without precedent to have more than one hurricane in the Atlantic hurricane area at one time, but the writer has never seen so many twins and triplets on the map of the western Atlantic before. Two of the maps with multiple storms are reproduced in figure 2.

During this busy hurricane season the Miami Hurricane Central issued 270 advisory bulletins and coordinated many others for release by other forecast centers. The total ran well over 300. The Navy dispatched 60 reconnaissance flights into hurricanes during this period, and the Air Force made slightly more; about 130 reconnaissance flights were completed in all. This is by far the greatest number of hurricane reconnaissance missions flown during any season since this observation method was introduced in 1943. This grilling pace was exhausting to both men and machines, including those who did the reconnaissance work and those at the Central who charted the storms and issued the advices.

INDIVIDUAL HURRICANES

Able—August 12–21. The first hurricane of the season was suspected on the afternoon of August 12 from general conditions several hundred miles northeast of the Leeward Islands. A reconnaissance plane located the developing

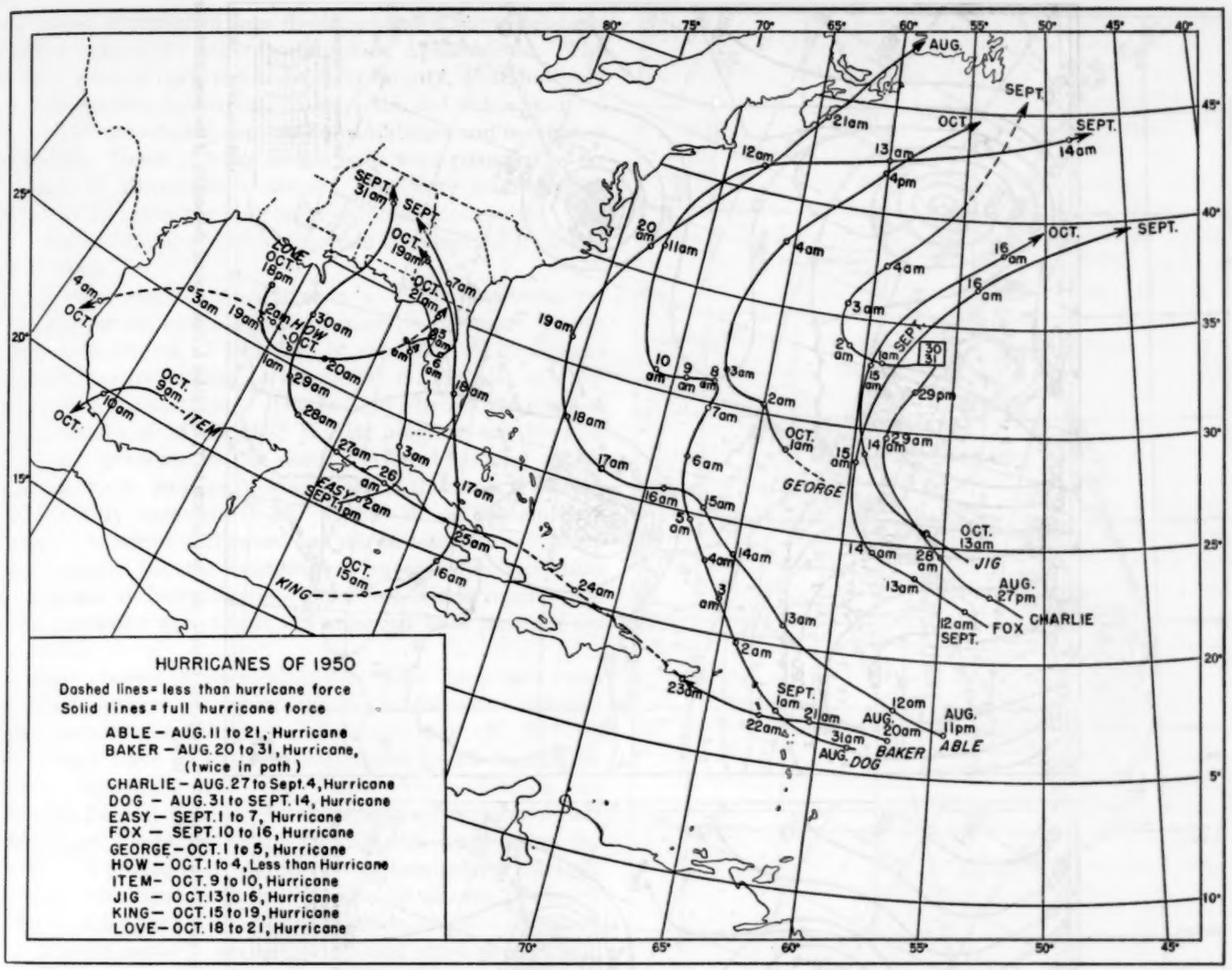
HURRICANES OF 1950
Dashed lines = less than hurricane force
Solid lines = full hurricane force
ABLE – AUG. 11 to 21, Hurricane
BAKER – AUG. 20 to 31, Hurricane, (twice in path)
CHARLIE – AUG. 27 to Sept. 4, Hurricane
DOG – AUG. 31 to SEPT. 14, Hurricane
EASY – SEPT. 1 to 7, Hurricane
FOX – SEPT. 10 to 16, Hurricane
GEORGE – OCT. 1 to 5, Hurricane
HOW – OCT. 1 to 4, Less than Hurricane
ITEM – OCT. 9 to 10, Hurricane
JIG – OCT. 13 to 16, Hurricane
KING – OCT. 15 to 19, Hurricane
LOVE – OCT. 18 to 21, Hurricane
ABLE
BAKER
CHARLIE
DOG
EASY
FOX
GEORGE
HOW
ITEM
JIG
KING
LOVE

FIGURE 1.—Tracks of the Atlantic hurricanes and tropical storms of 1950 named alphabetically in chronological order. Points on the paths are identified by date and time (a. m. or p. m.) of observation.

hurricane on the morning of the 13th near 21° N., 62° W. It soon increased to hurricane force and moved slowly on a variable northwesterly course which brought the center a short distance east of Cape Hatteras during the night of the 19th, and thence northeastward into Nova Scotia on the 21st. It caused strong winds on Cape Hatteras and Cape Cod, but hurricane force was not experienced on land, except in parts of Nova Scotia. The strongest winds reported in this hurricane were about 140 miles per hour and lowest pressure about 28.15 inches (953.3 mb.) recorded by aircraft at sea.

Baker—August 20–31. This hurricane appeared east of the Leeward Islands on August 20. It passed about over the island of Antigua during the night of the 21st with winds reported at 90 to 120 miles per hour. It progressed slowly west-northwestward losing force, and was only a minor disturbance on the 23d when it reached Puerto Rico, where strongest winds were 35 to 40 miles per hour. Thereafter, it was in the nature of a squally wave until the evening of the 25th when signs of another developing center were noted off the south Cuban coast. This center developed slowly, moved westward across the western tip of Cuba into the Gulf, made a curve to northward, and increased to hurricane force. Aircraft and ship reports on the afternoon of the 30th estimated strongest winds at about 115 miles per hour some distance south of the Alabama coast. This was the strongest reported in connection with this storm. It lost some force before moving inland during the night of the 30th between Mobile and Pensacola. Winds on the coast were 75 to 85 miles per hour; a total of about $2,550,000 damage to property and crops resulted from winds and tides in a zone from near Mobile to St. Marks, Fla. There were two tornadoes reported in connection with this hurricane, one

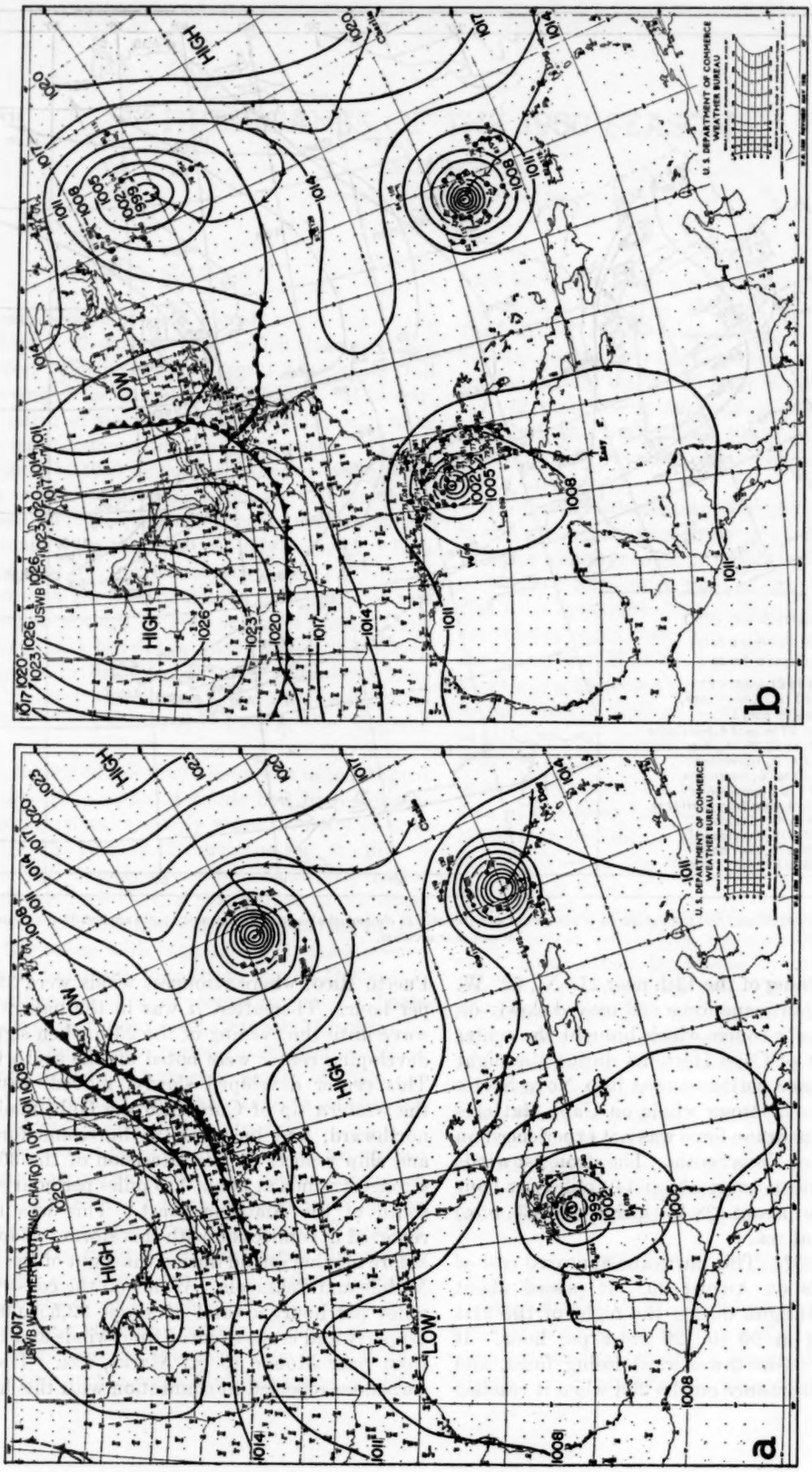

FIGURE 2.—(a) Section of surface chart for 0730 EST, September 2, 1950, showing three fully developed hurricanes, Dog, Easy, and George. (b) Chart for 0730 EST, September 4, 1950, showing the position of the same hurricanes 48 hours later.

of which demolished four dwellings and a store building, and damaged 11 other buildings at Apalachicola. The other tornado occurred in Jackson County, Fla., but only one home was destroyed. Heavy rain and winds resulted in heavy crop damage in southern Alabama and northwest Florida. Gusts of 50 miles per hour were recorded as far inland as Birmingham Airport, and were estimated as high as 75 miles per hour atop adjacent mountains. One person was killed and two injured in Birmingham by fallen live wires.

Charlie—August 27–September 4. This hurricane remained far out in the Atlantic during its life span. It was noted on August 27 near 23° N., and 53° W. whence it moved northwestward to about 29° N., 58° W. and recurved to the northeast. On the 30th when it had reached the vicinity of 34° N., 56° W., its progress was blocked by high pressure to the north. After becoming quasi-stationary, or perhaps making a loop in this area, it drifted very slowly westward to 34° N., 62° W. on September 2 when it resumed northward and northeastward movement and rapidly became extratropical several hundred miles southeast of Nova Scotia. Strongest winds reported in this hurricane were about 115 miles per hour recorded by aircraft.

Dog—August 31–September 14. This hurricane was located August 30 when the S. S. *Sibrodin* reported gale winds and falling pressure near 16.5° N., 57° W. It might have been the same storm whose beginnings were reported near the Cape Verde Islands on August 24, but there were no reports of it after it left the Cape Verde area until the *Sibrodin* reported on the 30th. It proved to be the most severe hurricane of the 1950 season, with winds estimated by aircraft at over 160 knots (184+ miles per hour) and waves 100 feet high. It moved on a northwesterly course and passed close to Antigua, Barbuda, and other islands of the northeastern Leeward group on September 1. Residents of Antigua, where highest winds were estimated at over 130 miles per hour and hurricane force lasted for 6 hours, reported it to be the most severe hurricane in the history of that island. Many homes and business houses were destroyed or damaged, crops destroyed, roads blocked by washouts and fallen trees, communications and power lines down, and many small craft wrecked. Two persons were drowned when their small boat capsized. The island of Barbuda also estimated winds of 130 miles per hour or greater, with equal or worse devastation than experienced at Antigua. Damage has been placed at over $1,000,000 on these small islands.

The hurricane continued to move slowly on a northwesterly course after leaving the Leeward Islands and curved northward toward Bermuda, but its progress was blocked about 200 miles southwest of Bermuda near 31° N., 67.5° W. on September 8. It drifted slowly westward for 2 days before resuming a north to northeast course, and finally turned eastward south of Nova Scotia and Newfoundland on the 13–14th. It gave strong winds on Cape Cod when

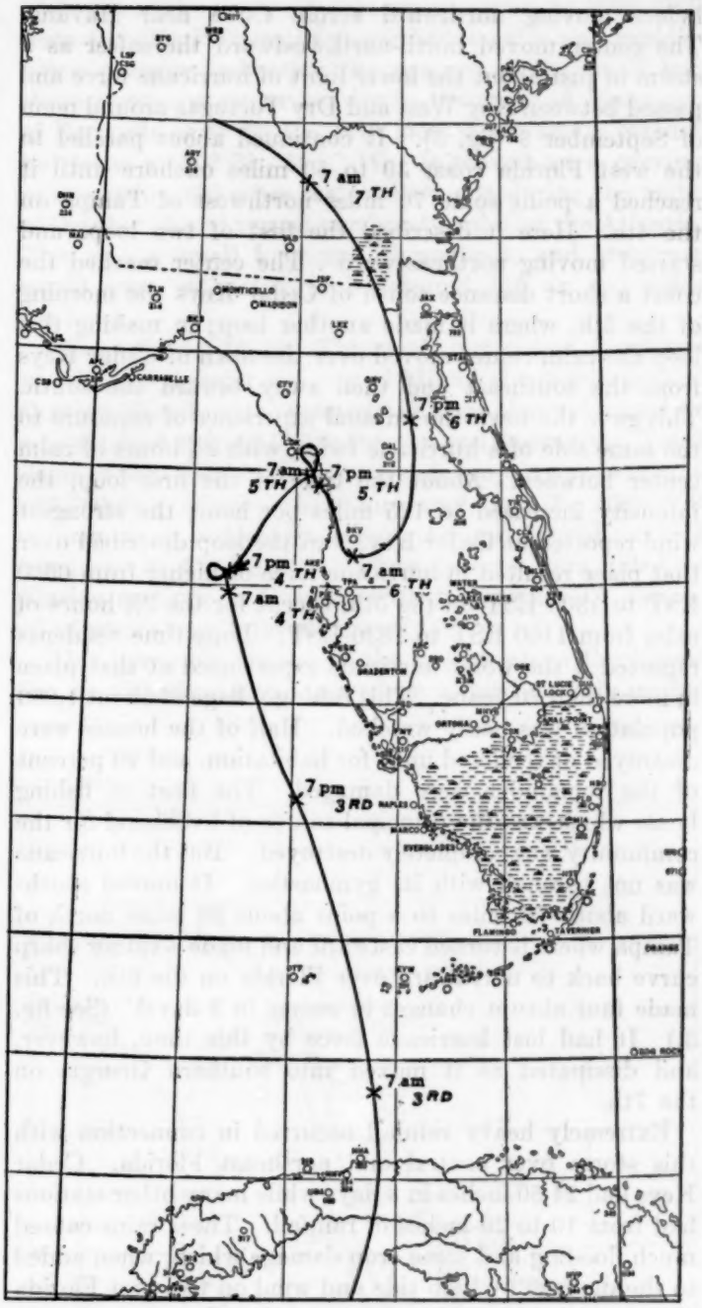

FIGURE 3.—Erratic path of hurricane Easy, September 1–7, 1950. Hourly readings from two radar sets confirm this track [1].

it was passing some distance offshore on the 12th, and the station at Nantucket reported gusts of near hurricane force. Although winds along the New England coast were less than full hurricane force, damage amounted to $2,000,000 and 12 lives were lost, 11 in capsized boats. It was fortunate that this great hurricane remained at sea and did not seriously affect other coastal areas for it was indeed a giant of potential destruction.

Easy—September 1–7. Long before the Atlantic giant was out of the way, the next hurricane developed in the northwestern Caribbean Sea south of the Isle of Pines on September 1. It remained nearly stationary for 2 days,

before moving northward across Cuba near Havana. The center moved north-northwestward thereafter as a storm of just about the lower limit of hurricane force and passed between Key West and Dry Tortugas around noon of September 3 (fig. 3). It continued about parallel to the west Florida coast 30 to 50 miles offshore until it reached a point some 70 miles northwest of Tampa on the 4th. Here it described the first of two loops and started moving northeastward . The center reached the coast a short distance south of Cedar Keys the morning of the 5th, where it made another loop; in making this loop the calm center moved over the town of Cedar Keys from the southeast and then away toward the south. This gave the town the unusual experience of exposure to the same side of a hurricane twice, with 2½ hours of calm center between. About the time of the first loop, the intensity increased to 125 miles per hour, the strongest wind reported at Cedar Keys, but the loop described over that place resulted in hurricane force or higher from 0600 EST to 1800 EST on the 5th, except for the 2½ hours of calm from 1100 EST to 1330 EST. Long-time residents reported it the worst hurricane experienced at that place in more than 70 years. This fishing village of about 1,000 population was badly wrecked. Half of the houses were destroyed or rendered unfit for habitation, and 90 percent of the remainder were damaged. The fleet of fishing boats which was the principal source of livelihood for the community was completely destroyed. But the hurricane was not through with its gymnastics. It moved southward about 70 miles to a point about 30 miles north of Tampa where it turned eastward and made a rather sharp curve back to northward over Florida on the 6th. This made four abrupt changes in course in 3 days! (See fig. 3.) It had lost hurricane force by this time, however, and dissipated as it moved into southern Georgia on the 7th.

Extremely heavy rainfall occurred in connection with this storm over central and northeast Florida. Cedar Keys had 24.50 inches in 3 days while many other stations had from 10 to 20 inches of rainfall. These rains caused much flooding and some crop damage which, when added to the damage by high tide and wind on the west Florida coast, amounted to about $3,300,000. Two persons were killed by fallen live wires and 27 others were injured in various ways. The small damage figure is due to the sparsely settled area where the worst part of the hurricane occurred. The lowest pressure reported was 28.30 inches (958.3 mb.) at Cedar Keys.

The warning service in connection with this hurricane was very good despite its erratic course; however, warnings were issued for a larger area than actually experienced hurricane winds. The extremely erratic movement, which presented the most difficult forecasting problems that we have encountered, has been discussed in detail by Gentry [1].

Fox—September 10–16. This hurricane was discovered by aircraft reconnaissance on September 10 near 19° N., 50° W., or about 1,000 miles east of Puerto Rico. At that time it was a small hurricane with winds estimated at 70 to 80 miles per hour. The wind speed increased to about 140 miles per hour as it moved in a curving path toward the northwest and north during the next few days. It passed more than 300 miles east of Bermuda on the 15th, and thereafter moved rapidly northeastward over the Atlantic. This hurricane remained small throughout its course, but maintained maximum velocities of about 140 miles per hour until it moved out of range of reconnaissance.

George—October 1–5. A strong easterly wave was noted on September 27 over the Atlantic far to the southeast of Bermuda. It developed a large low pressure system that drifted slowly northwestward, but daily reconnaissance failed to find a storm center of strong circulation until October 1. At 0730 EST on the 1st, the S. S. *Alcoa Regasus*, about 170 miles south of Bermuda at 29.5° N., 64.4° W., reported a southwest wind 65 miles per hour, which indicated hurricane development. An airplane later in the day found the center with highest wind about 100 miles per hour. It moved slowly northward until the morning of October 2 with a threat to Bermuda since it was only 90 to 100 miles away. It changed course, however, and swung westward far enough to miss Bermuda before resuming a northward and northeastward course. It passed south of Newfoundland on the 5th. The strongest wind reported was about 110 miles per hour on the morning of October 4 when the center was near 39° N., 65° W.

How—October 1–4. A tropical storm of less than hurricane force developed in the Gulf of Mexico October 1 near 25.5° N., 89° W. It moved on a northwest, west, and then southwest course and entered Mexico north of Tampico on the 4th. The strongest winds reported in connection with this storm were about 55 miles per hour. Squally winds of 45 to 55 miles per hour prevailed during most of its life in the Gulf of Mexico, and were confined mostly to the northern semicircle of the disturbance. This was the only disturbance of the season that did not develop hurricane force.

Item—October 8–10. This small hurricane began to develop on the 8th in the Gulf of Mexico northwest of the Yucatan Peninsula. On the morning of the 9th, a reconnaissance plane located the small center with 90 miles per hour winds at 21° N., 94° W., about 200 miles northeast of Vera Cruz, Mexico. It moved southwestward and entered Mexico a short distance south of Vera Cruz on the morning of the 10th. The strongest wind reported was 110 miles per hour at Vera Cruz. Damage in Vera Cruz and vicinity was reported in the press as "heavy" but no estimate of the amount of damage or number of casualties has been received.

Jig—October 13–16. At 0800 EST on October 13 the S. S. *Rio Primero* reported a northeast gale wind and rapidly falling pressure at 27° N., 57° W., which indicated that a hurricane center was in the vicinity of 25.5° N.,

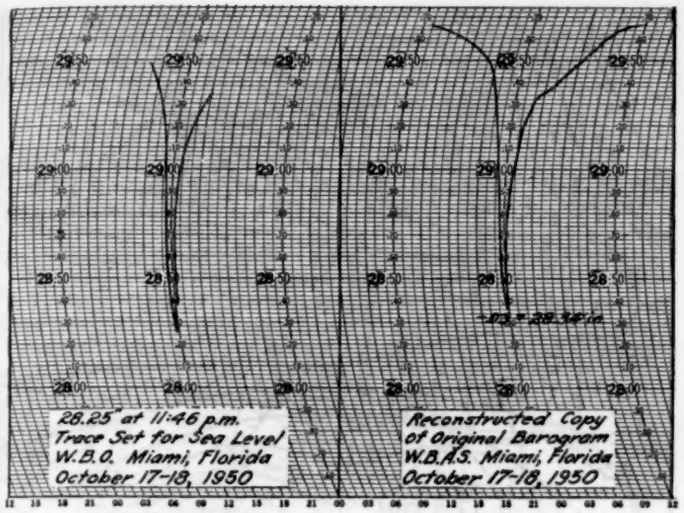

FIGURE 4.—Barogram traces for 2 recording stations in Miami, October 17–18, 1950, during passage over city of hurricane King.

56.5° W. at the time. A subsequent report at 1000 EST from the *Rio Primero* gave northwest gales and rapidly rising pressure indicating the passage of the small but sharp hurricane center nearby to the east. A plane out of Bermuda early on the 14th located the small, mature hurricane at 29° N., 59.3° W. It moved on a curving path passing 300 miles east of Bermuda during the night of October 14 and turned northeastward over the Atlantic. This was a small hurricane throughout, and strongest winds were estimated to be around 115 or 120 miles per hour.

King—October 15–19. This small, but violent, hurricane passed directly over the city of Miami about midnight of October 17 and caused property damage that amounted to an estimated $15,000,000 in the city and its vicinity. Total damage for Florida in crops and property was about $27,750,000, which, when increased by the $250,000 damage done in Georgia, brings the grand total for this hurricane to $28,000,000. Three persons were killed in Florida and one in Georgia, with injuries to 199 others, 16 of whom were injured seriously.

This hurricane formed in the northwestern Caribbean Sea on October 15 and moved on a northeasterly course

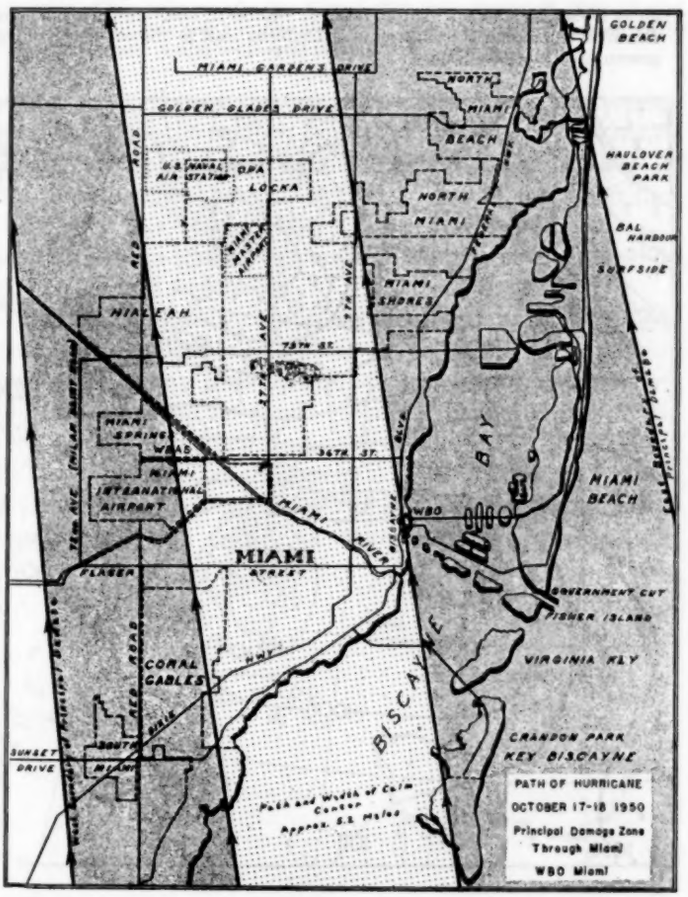

FIGURE 5.—Map showing hurricane King's path across Miami and vicinity. Darker shading indicates areas of greatest damage.

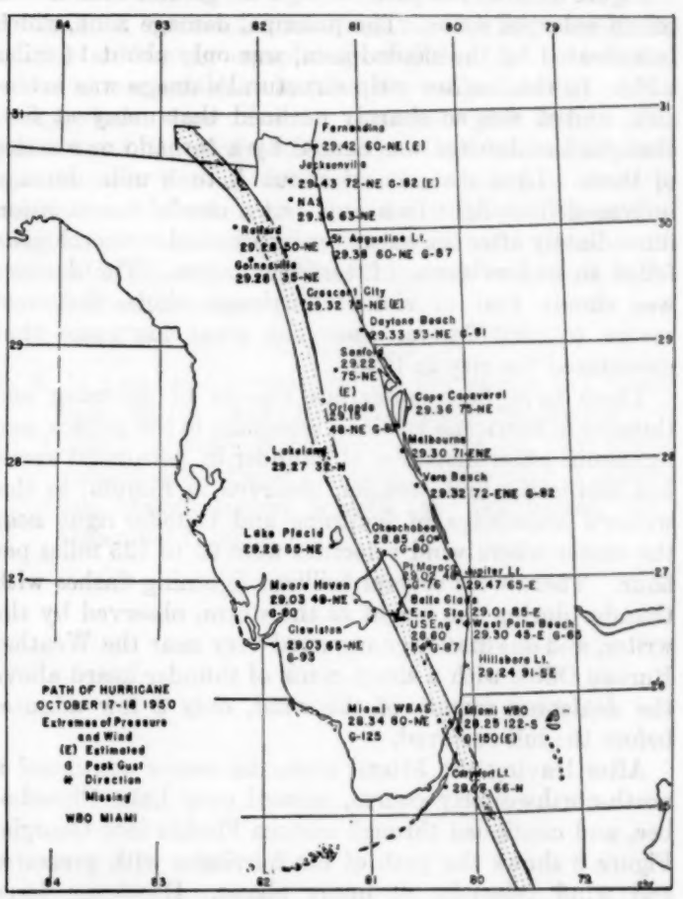

FIGURE 6.—Path of hurricane King across Florida showing pressure and wind velocity (m. p. h.) at selected points.

at first, past the western end of Jamaica, then turned northward across Cuba just west of Camaguey during the night of the 16th. It was a small hurricane at that time; strongest winds at Camaguey were only around 65 miles per hour. The course turned more to north-northwest as it moved through the Florida Straits on the 17th. A reconnaissance plane entered the "eye" at about 0900 EST on the 17th north of the Cuban coast and found strongest winds about 85 to 90 knots with some gusts estimated at 100 knots. The minimum pressure in the center at that time was 988.0 mb. (29.18 in.), and the "eye" was about 20 miles in diameter. When it reached Miami at midnight, the central pressure was 955.0 mb. (28.20 in.), and the central calm area was only about 5 miles in diameter. Maximum sustained winds had increased to 122 miles per hour with gusts of about 150 miles per hour. Thus in the period from around 0900 EST to midnight there was considerable intensification; central pressure fell 0.98 inch (33.2 mb.), the wind increased greatly, and the central "eye" contracted from 20 miles to 5 miles in diameter. The barograph traces for the two recording stations in Miami are shown in figure 4. They indicate the small, intense vortex. These stations were on the edges of the "eye," with center midway between them.

Figure 5 shows the path through the greater Miami area on an enlarged scale. The principal damage zone, which is indicated by the shaded area, was only about 14 miles wide. In this narrow strip structural damage was extensive, and it was so sharply outlined that many at first thought the damage was caused by a tornado or a series of them. In a distance of about ¼ to ½ mile damage increased from light to heavy, but a careful examination immediately after the storm by experienced meteorologists failed to find evidence of tornadic action. The damage was simply that of violent hurricane winds, the most severe to visit Miami since the great hurricane that devastated the city in 1926.

There have been numerous reports of lightning and thunder in hurricane vortices, especially in the tropics, and numerous other instances of thunder in peripheral areas, but this is the first occasion observed in Florida, to this writer's knowledge, of lightning and thunder right near the center where wind velocities were 95 to 125 miles per hour. There were several brilliant lightning flashes with thunder during the height of the storm, observed by the writer, and one discharge occurred very near the Weather Bureau Office with a sharp crack of thunder heard above the deafening scream of the wind, only a few minutes before the lull occurred.

After leaving the Miami area, the center continued a north-northwesterly course, crossed over Lake Okeechobee, and continued through eastern Florida into Georgia. Figure 6 shows the path of the hurricane with pressures and wind velocities at many places. Hurricane force winds in squalls extended nearly to the Georgia line, espe-

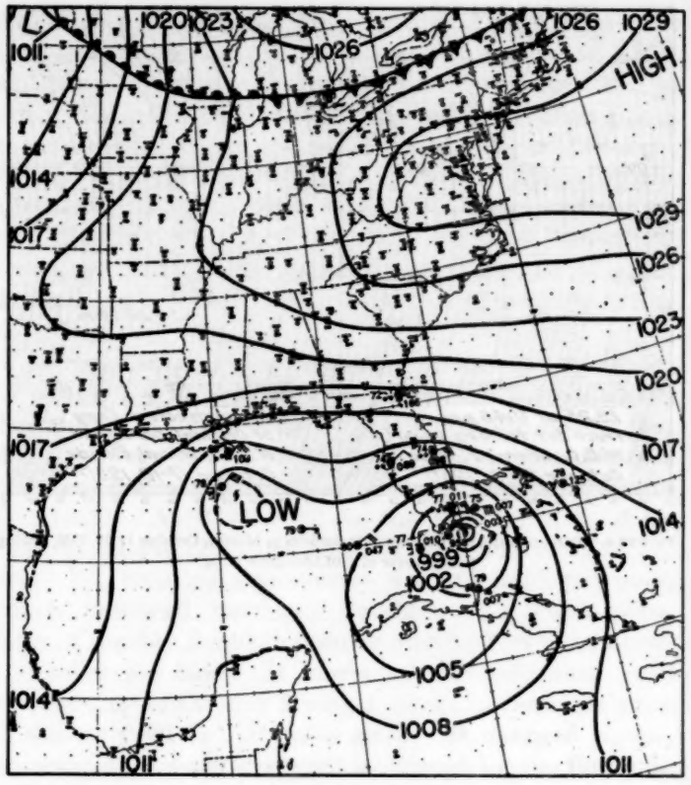

FIGURE 7.—Section of surface chart for 1930 EST October 17, 1950, showing beginning of formation of a second hurricane south of Louisiana coast in offshoot trough of low pressure from hurricane King.

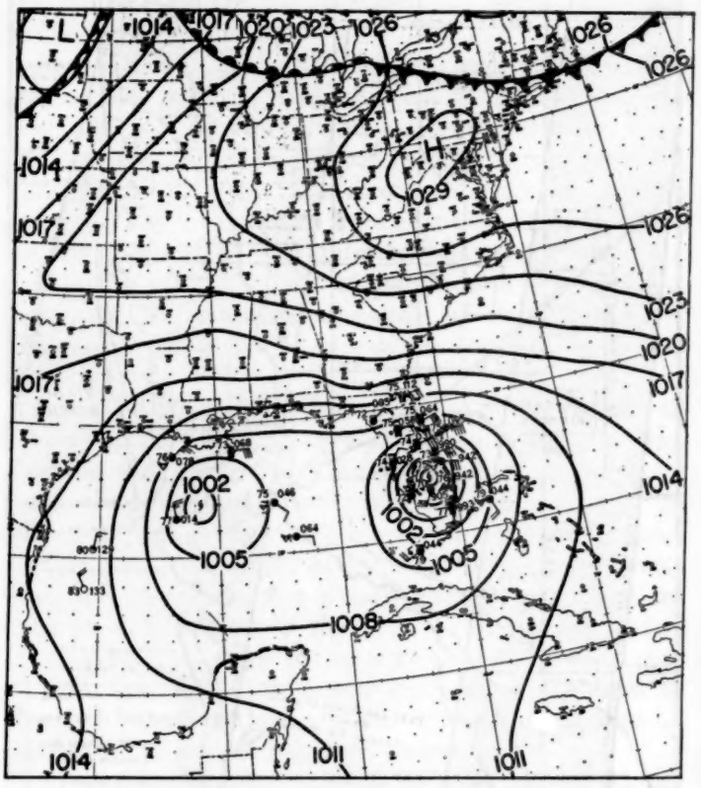

FIGURE 8.—Chart 12 hours later than figure 7 (0730 EST, October 18, 1950) showing development of second hurricane (Love).

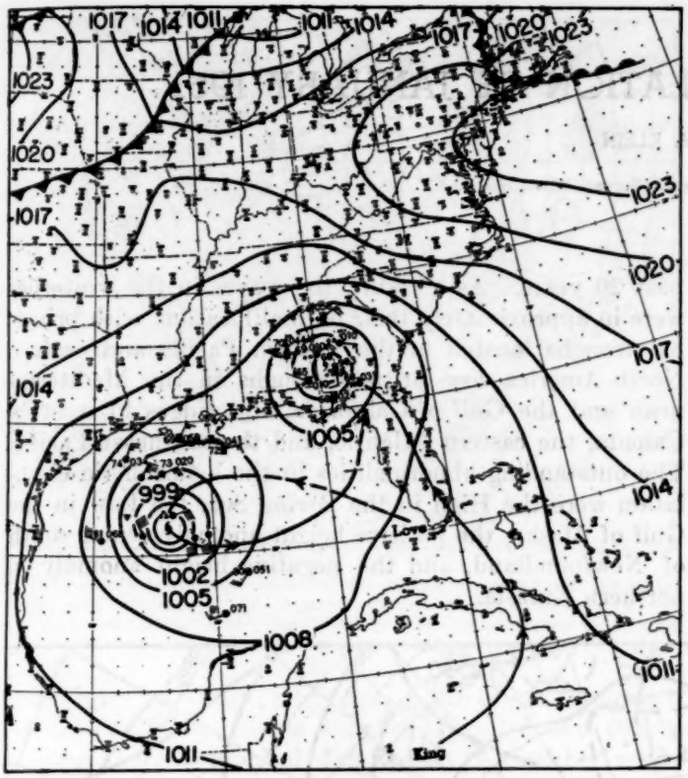

FIGURE 9.—Chart 24 hours later than figure 8 (0730 EST, October 19, 1950). Second storm (Love) is now near hurricane force while hurricane King is filling over southwestern Georgia. Tracks are inserted to indicate complete path of each.

cially along the Atlantic coast, and considerable damage resulted in all the eastern counties of Florida. Very heavy squalls extended out a considerable distance northeast of the barometric center after it reached the middle peninsula. By this time, however, the center was beginning to spread out and break up, and winds were weakening on the south and west sides.

The warning service was excellent and provided ample time for all possible hurricane preparation. This doubtless saved many lives and much property. A hurricane alert was ordered for south Florida 36 hours ahead of the storm and hurricane warnings were ordered 18 hours ahead of the hurricane winds by the Miami Hurricane Center. Despite the good warning service, many people remained complacent and failed to take adequate precautions. This resulted in increased damage when glass windows blew out, and the interiors and contents of buildings were damaged by rainwater.

Love—October 18–21. The last hurricane of this most trying season certainly belied its romantic designation. It was more bewildering and exasperating, if possible, than the others of the season's disturbances. It began forming in the Gulf of Mexico south of the Louisiana coast at the time the severe hurricane was moving northward through Florida on the 18th, and in some respects was an "offshoot" of it. (See figs. 7, 8, and 9.) As the Florida hurricane was moving north-northwestward from the Caribbean Sea, an elongation of low pressure extended ahead of it over Florida. As the hurricane progressed this pressure trough moved northwest and west, with a tendency to move counter-clockwise around the hurricane. On the 18th (fig. 8) it developed a center of circulation of its own south of the Louisiana coast. This center continued its counter-clockwise movement and swung down into the central Gulf on the 19th (fig. 9) and increased to hurricane force. On the 20th, aircraft reported maximum winds of 75 to 85 knots (85 to 98 miles per hour), especially in the northeastern quadrants. The movement by this time had completed the swing to the east and northeast, which caused it to offer a threat of hurricane winds to the upper west Florida coast. During the night of the 20th, however, it lost force rapidly, apparently due to dry air having completely encircled the center, and when it reached the coast on the early morning of the 21st, winds were of only moderate gale force. The presence of dry air from the West Gulf States had been noted on its western side since the time of its development, but it continued to increase in force, despite this, until the dry air had worked its way around to the south and east of the center. When this stage was reached, the loss of intensity was rapid.

REFERENCES

1. R. C. Gentry, "Forecasting the Formation and Movements of the Cedar Keys Hurricane, September 1–7, 1950," *Monthly Weather Review*, vol. 79, 1951 (to be published). Paper presented at meeting of American Meteorological Society, at Tallahassee, Fla., December 6, 1950.

THE WEATHER AND CIRCULATION OF JANUARY 1951

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CIRCULATION FEATURES

The circulation pattern at the 700-mb. level during January 1951 shown in figure 1 differed only slightly from the long period "normal" for January. For the first time since this series of articles was initiated a year ago, the monthly mean 700-mb. height anomaly did not exceed 220 feet in absolute magnitude anywhere in the Northern Hemisphere. In the North American region January height anomalies as small as those observed this year have occurred only once previously (1939) in the past 20 years. As a result, the waves in the westerlies were in approximately their normal location, with principal troughs located in the western Pacific and eastern North America, low latitude troughs in the Mediterranean and the Gulf of California, and ridges in western Canada, the eastern Atlantic, and the southeast Pacific. The outstanding abnormalities in the hemispheric circulation were the High in the Bering Sea, the Low in the Gulf of Alaska, the positive height anomaly center south of Newfoundland, and the negative height anomaly in northern Eurasia.

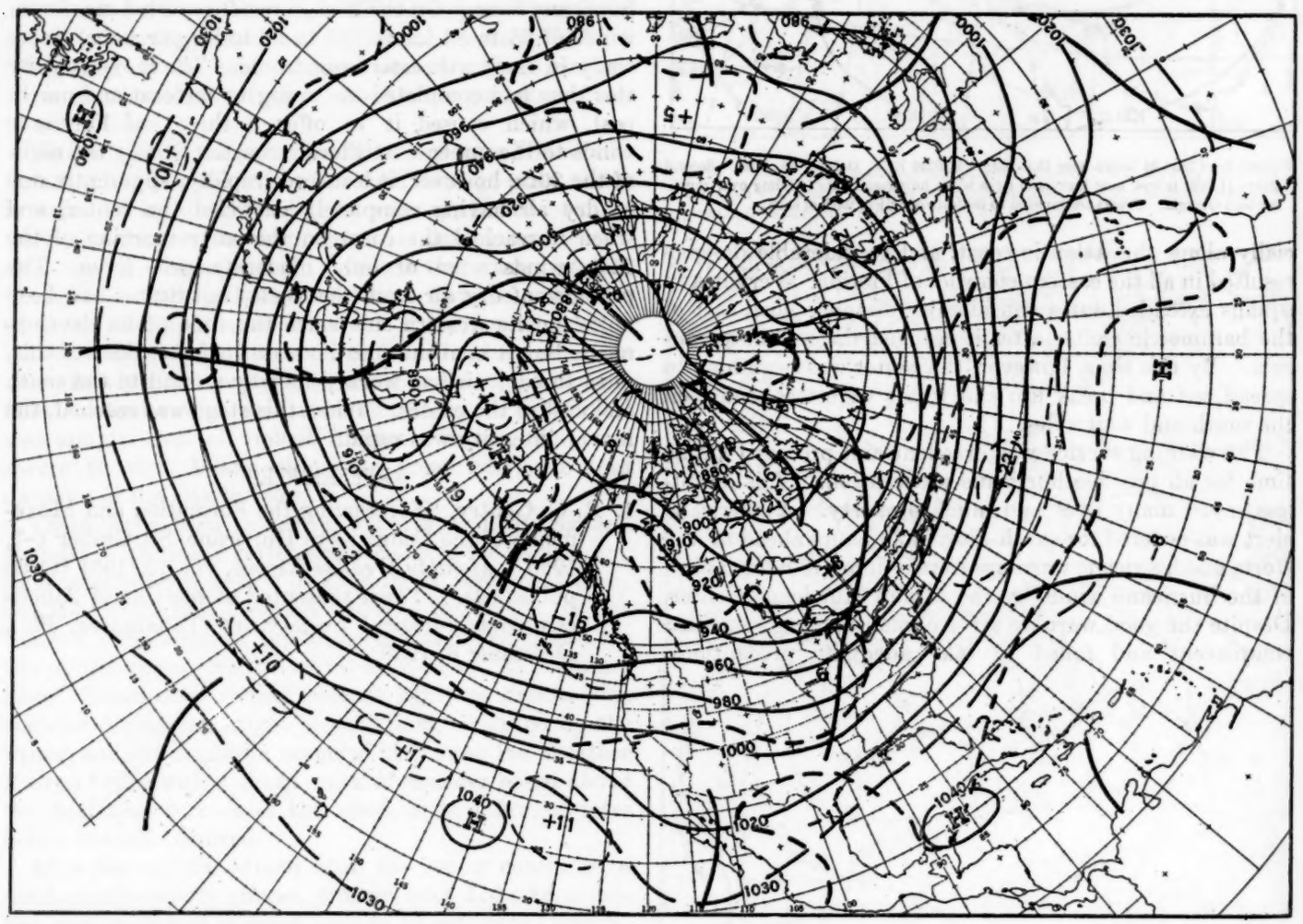

FIGURE 1.—Mean 700-mb. chart for the 30-day period January 2-31, 1951. Contours at 200-ft. intervals are shown by solid lines, intermediate contours by lines with long dashes, and 700-mb. height departure from normal at 100-ft. intervals by lines with short dashes with the zero isopleth heavier. Anomaly centers and contours are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

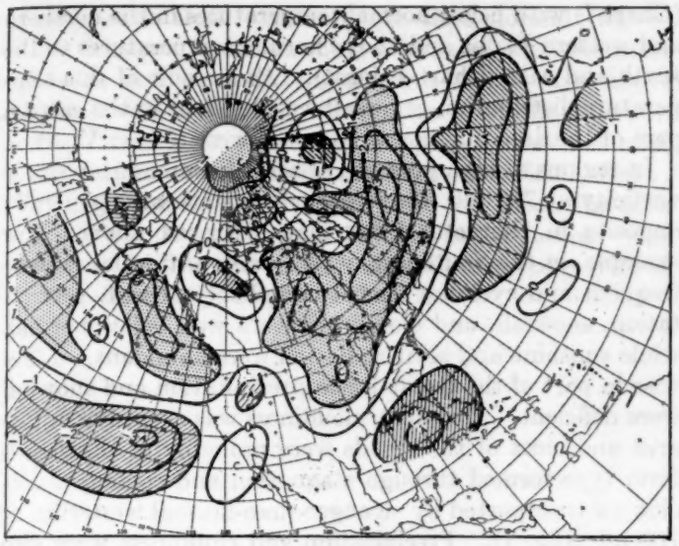

FIGURE 2.—Vertical component of mean relative geostrophic vorticity at 700 mb. for the 30-day period January 2-31, 1951. Areas with cyclonic vorticity in excess of 1×10^{-5} per second are stippled and labeled C at the center; areas with anticyclonic vorticity less than -1×10^{-5} per second are cross hatched and labeled A at the center.

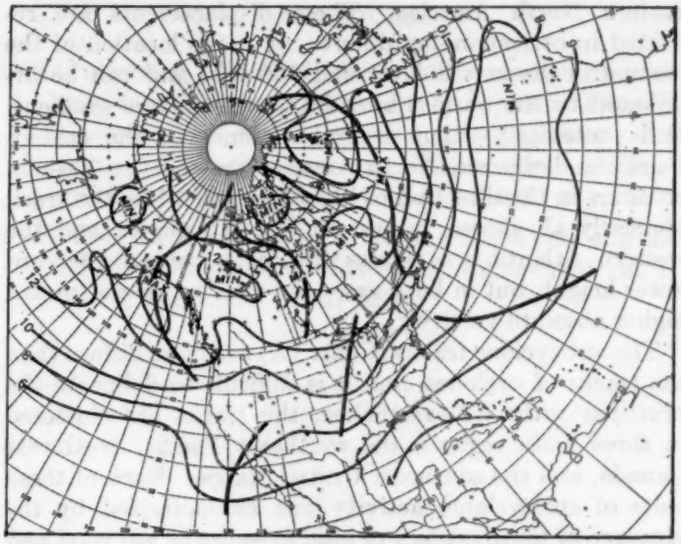

FIGURE 3.—Vertical component of mean absolute geostrophic vorticity at 700 mb. for the 30-day period January 2-31, 1951. Isopleths at intervals of 2×10^{-5} per second are shown by solid lines and maximum latitude ridge locations by heavy solid lines. Centers of maximum and minimum absolute vorticity are labeled MAX and MIN respectively.

In order to throw additional light on this month's circulation, figure 1 was supplemented by two charts showing the geographical distribution of monthly mean geostrophic vorticity at the 700-mb. level. Figure 2 gives the vertical component of the mean vorticity relative to the earth's surface, computed at standard 5° intersections of latitude and longitude from the 700-mb. contour field (fig. 1).[1] The vorticity values are considerably smaller in magnitude than corresponding values computed from daily sea level maps [1], nevertheless a well-defined pattern is evident. The influence of wind shear is indicated by the fact that cyclonic vorticity generally prevails north of the latitude of the mean 700-mb. jet stream (40°–45° N.) and anticyclonic vorticity to the south. The effect of contour curvature is also noticeable. As one would expect, regions of cyclonic vorticity in figure 2 generally correspond with regions of cyclonic curvature in figure 1, while anticyclonic vorticity prevails in regions of anticyclonic curvature. Even more striking is the close connection between relative vorticity at 700 mb. and isobar curvature at sea level, as can be seen by comparing figure 2 with Chart XI[2]. Centers of anticyclonic vorticity at 700 mb. are superimposed on centers of high pressure at sea level in the southeast Pacific, northwest Canada, Great Basin of the United States, and Azores Islands, while areas of cyclonic vorticity and sharp pressure troughs almost coincide in the western Aleutians, Gulf of Alaska, Hudson Bay, Mississippi Valley, and North Atlantic. Thus the field of relative vorticity at 700 mb. appears to be a good index of the mean sea level circulation This is particularly true of monthly mean maps where quasi-barotropic conditions usually prevail.

Figure 3 gives the vertical component of the absolute geostrophic vorticity for the month of January 1951. It was prepared by simply adding the Coriolis parameter to values of the relative vorticity computed for figure 2. As a result the absolute vorticity generally increases in magnitude with increasing latitude and the isopleth pattern is primarily sinusoidal in character. The lines of absolute vorticity in figure 3 parallel the contours in figure 1 so that ridge lines on the former chart, drawn through the points of maximum vorticity along latitude circles, generally coincide with trough lines on the latter chart, drawn through points of minimum height along latitude circles. When used in conjunction with the mean circulation at 700 mb. (fig. 1) and sea level (Chart XI), figure 3 may be of assistance in delineating the prevailing tracks of migratory cyclones and anticyclones, since Kuo [2] has shown that (on daily maps at least) cyclonic vortices should tend to be driven toward regions of higher absolute vorticity and anticyclonic vortices toward regions of lower absolute vorticity.

For example, Chart X shows that there were two principal tracks of cyclones during the month, one from the Gulf of Alaska along the border between the United States and Canada through Labrador to Iceland, and the other from the southern half of the Great Plains through the Great Lakes and the St. Lawrence Valley to Iceland. Both paths correspond in most respects to the axes of maximum vorticity, except that the cyclone track is displaced slightly to the south of the vorticity maximum in western North America and slightly to the east in

[1] Numerical values of vorticity were computed by means of a simple method to be described in a forthcoming report by E. J. Aubert of the Extended Forecast Section of the U. S. Weather Bureau.

[2] See Charts I–XV following p. 26 for analyzed climatological data for the month.

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eastern North America. These displacements are reflected in corresponding differences in the location of the mean troughs at sea level and 700 mb. and can be attributed to the normal horizontal temperature gradient. It is noteworthy that several cyclones in the eastern Pacific and western North America crossed the 700-mb. contours in the direction of higher height, while the track of nearly all storms in eastern North America and the western Atlantic was across the mean contours toward lower height, but in both cases the crossings were toward higher absolute vorticity.

The anticyclone tracks (Chart IX) are more diffuse than the tracks of cyclones, and it is difficult to delineate the principal paths. Nevertheless, the tracks are clustered in three main regions, the southeast Pacific, northwest Canada, and the southeast United States. Each of these seats of anticyclonic activity was characterized by the presence of mean centers of high pressure at sea level and anticyclonic vorticity at 700 mb. On the other hand, areas of low pressure and cyclonic vorticity in the Gulf of Alaska, north Atlantic, and eastern Canada were notably free of anticyclonic activity. It may also be significant that the anticyclone tracks crossed the mean 700-mb. flow toward regions of lower absolute vorticity in both western North America where they moved mainly southward, and eastern North America and the Atlantic, where they moved mostly eastward.

THE WEATHER

The circulation features discussed above were reflected in this month's weather in the United States. Along the principal cyclone track in the lower Mississippi and Ohio Valleys and the Northeast, just to the east of both the axis of maximum cyclonic vorticity and the mean troughs at sea level and aloft, precipitation generally totaled more than four inches (Chart II) and exceeded the seasonal normal (Chart III, A and B). Much of this precipitation was in the form of snow (Chart IV) which fell in greater than normal quantity (Chart V, A). In addition, average cloudiness in these areas exceeded 60 percent (Chart VI) as well as the seasonal normal (Chart VII, A), sunshine was less than half of the maximum possible (Chart VII, B), and there was less solar radiation than in adjacent regions (trough in isopleths of Chart VIII). Generally similar conditions prevailed in the northwestern quarter of the country, along the principal cyclone track from the Gulf of Alaska, but the various charts present a more irregular appearance in that area because of mountain effects. Precipitation and cloudiness were also excessive in a zonal band extending from Colorado and northern New Mexico eastward to Missouri and Arkansas, as several old disturbances entering the country from the Pacific regenerated in this area (Chart X). This cyclogenesis was favored by topography and the proximity of a mean trough at sea level (Chart XI), cyclonic vorticity at 700 mb. (fig. 2), and a large horizontal temperature gradient (Chart I) with below normal temperatures in the northern and western Plains and above normal temperatures to the south and east (Chart I, inset). As a result of this temperature distribution, snowfall was deficient in the eastern part of the area but excessive in the west (Chart V, A).

In regions of high pressure at sea level and anticyclonic vorticity at 700 mb. the weather elements were generally opposite in character from that discussed above. For example, in the Southeast, where daily anticyclones were frequent and cyclones almost completely absent, precipitation, snowfall, and cloudiness were well below normal, while sunshine and solar radiation were abundant. Likewise in part of the Great Basin precipitation and snowfall were deficient. However, cloudiness was excessive in this area and most of the clouds were probably of the stratiform type formed through stagnation and cooling of Pacific air transported by stronger-than-normal westerlies at 700 mb. (fig. 1). Precipitation and cloudiness were also below seasonal normals in most of Texas and in parts of the northern Plains. In portions of these regions no precipitation at all was recorded during the entire month (Chart II). The drought in Texas was due primarily to the "rain shadow effect" as the State was just south of the strongest belt of westerlies at 700 mb. as well as the principal cyclone track at sea level. Dry weather in the northern Plains was accompanied by anticyclonic conditions at sea level, as attested by the anticyclone tracks (Chart IX) and the presence of both a pronounced mean ridge (Chart XI) and positive pressure anomalies (Chart XI, inset).

The surface temperature anomaly observed in the United States during January 1951 (Chart I, inset) reflected the near-normal character of the 700-mb. circulation for the month (fig. 1). The Northeast was the only large area whose average temperature departed from normal by more than 4° F. This district was abnormally warm primarily because its mean air flow was from a southerly direction relative to normal at both sea level (Chart XI, inset) and 700 mb. In addition 700-mb. heights were somewhat above the seasonal normal. Similar conditions were associated with the warm weather observed in most of the southern and eastern portions of the country. West of the Continental Divide most temperatures were slightly above normal because of the dominance of mild Pacific air transported by stronger-than-normal westerlies at 700 mb. These positive temperature anomalies were larger in the South, where 700-mb. heights were above normal, than in the North, where negative height anomalies were observed.

The only extensive areas with below normal temperatures were the northern and western Plains where 700-mb. heights were generally below normal. Cold polar continental air was carried into these regions by several anticyclones which moved south from a mean High in northwest Canada, at the center of which sea level pressure was 7 mb. above normal (Chart XI, inset). However,

the westerlies aloft were stronger than normal (fig. 1) so that frequent foehn warming alternated with the polar outbreaks and caused temperatures to average above normal in the lower and western parts of the Missouri Valley. The most extreme example of this occurred during the last week of the month at Goodland, Kans., where the temperature dropped from 79° F. on the 26th to 3° F. on the 27th, or a 76° fall in 18 hours. (See article by Miller and Gould on following pages for a detailed description of this cold wave.)

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2. H. Kuo, "The Motion of Atmospheric Vortices and the General Circulation", *Journal of Meteorology*, vol. 7, No. 4, Aug. 1950, p. 247–258.

NOTICE OF CHANGE IN CLIMATOLOGICAL CHARTS

The charts showing weather data for the month which appear at the back of each issue of the Review have been revised and augmented effective with this issue. Most of the maps showing departures of the weather elements from normal have been enlarged and new maps showing percentages of normal amounts of precipitation, snowfall, and cloudiness have been added. Another new chart giving monthly solar radiation data has been inserted. The former Chart IV "Percentage of Clear Sky between Sunrise and Sunset" has been reversed and now appears as Chart VI "Percentage of Cloudiness between Sunrise and Sunset".

THE EXTENSIVE COLD AIR OUTBREAK OF JANUARY 24–31, 1951

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INTRODUCTION

During the last week of January a cold air outbreak occurred in the United States which, although setting few records for severity, was unusual for several reasons. (1) The intensity of the anticyclone over northwest Canada associated with the outbreak reached a central value of approximately 1065 mb. which is close to the record for the Western Hemisphere.[1] (2) With the exception of the extreme southeastern portion, the entire country was covered by very cold air and, by February 2, even this remaining section was overrun. (3) The southward progress of the cold front was appreciable only at the lowest levels above the surface, principally impelled by subsidence. This resulted in a very shallow, very cold air mass covering much of the country during several days. Overrunning by warm, moist air, above this shallow cold air, gave rise to widespread precipitation and, especially, to hazardous sleet and freezing rain east of the Rockies.

[1] Few records are available on the maximum intensity of anticyclones over Canada. Connor [1] states that Arctic stations have reported as high as 31.0 in. (1050 mb.). A value of 1070.1 mb. was recorded at Dawson, Yukon on Jan. 6, 1909. U. S. Weather Bureau frequency charts [2] indicate that there was only one occurrence of a value of 1062.5 mb. or more during the 10-year period 1929–38. Generally accepted world record is 1079.0 mb. which occurred at Barnaul, Siberia (53° N., 84° E.) on January 23, 1900 [3].

HISTORICAL DEVELOPMENT

The surface chart of January 26, 1951, 0030 GMT (fig. 1), represents the synoptic situation shortly before the intense cold air made its incursion into most of the United States and before the High in Canada reached its maximum intensity. The weak Low in the northwest corner of the country moved eastward from the Pacific Ocean and helped initiate the cold outbreak. Prior to this time, however, there were other important developments. The High over northwest Canada had been increasing slowly in intensity since January 22

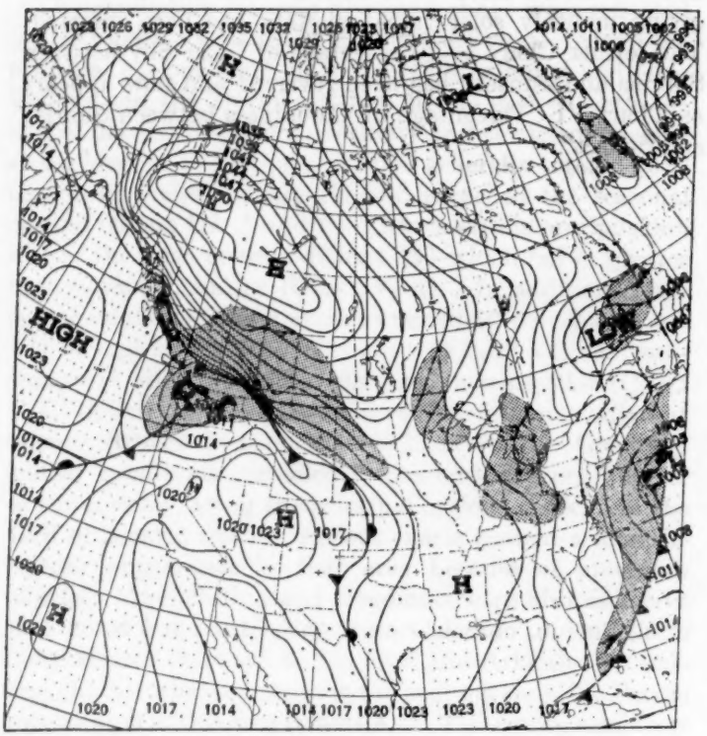

FIGURE 1.—Surface weather chart for 0030 GMT, January 26, 1951. Shading indicates areas of active precipitation.

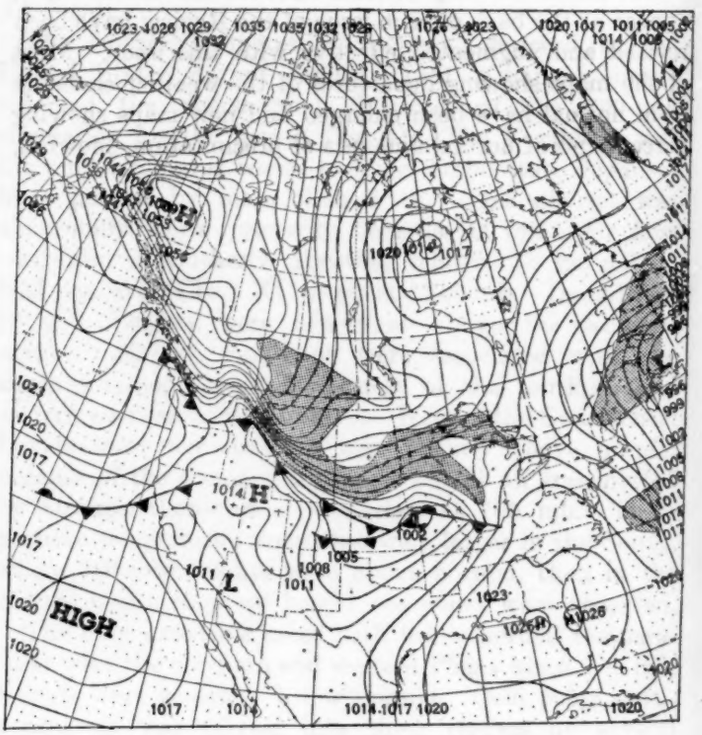

FIGURE 2.—Surface weather chart for 0030 GMT, January 27, 1951.

(table 1) and the ridge which is shown over the Gulf of Alaska (fig. 1) replaced a rapidly-filling, once intense, cyclone.

On January 27 (fig. 2), the Low from the Pacific was moving rapidly eastward across the Plains until, on the following day (fig. 3), it dissipated off the Atlantic coast. By then the cold air had extended across the entire country but its southward progress, except in the Central Plains region, had been confined to the area north of 45° N. It should be noted also that on that day the High over northwest Canada reached its maximum intensity of approximately 1065 mb.

On January 29 (fig. 4), a High cell appeared in Montana which moved rapidly eastward on the following days. The erratic movement of this center as it passed over the Great Lakes was interesting in that it dramatically emphasized the importance of these inland water bodies as a heat source during the winter months. As the High center approached Lake Michigan on January 30 (fig. 5), it decelerated markedly and another center began to form to the northeast of Lake Huron. By January 31 (fig. 6), a remnant of the western center continued to persist west of Lake Michigan even as the new center began accelerating toward the east. An examination of the 700-mb. chart for these days (figs. 14 and 15) indicates that the cold air continued its eastward movement uninterruptedly. It must be assumed then that the apparent "jump" of the surface center was caused by warming in the lowest layers in the Great Lakes area.

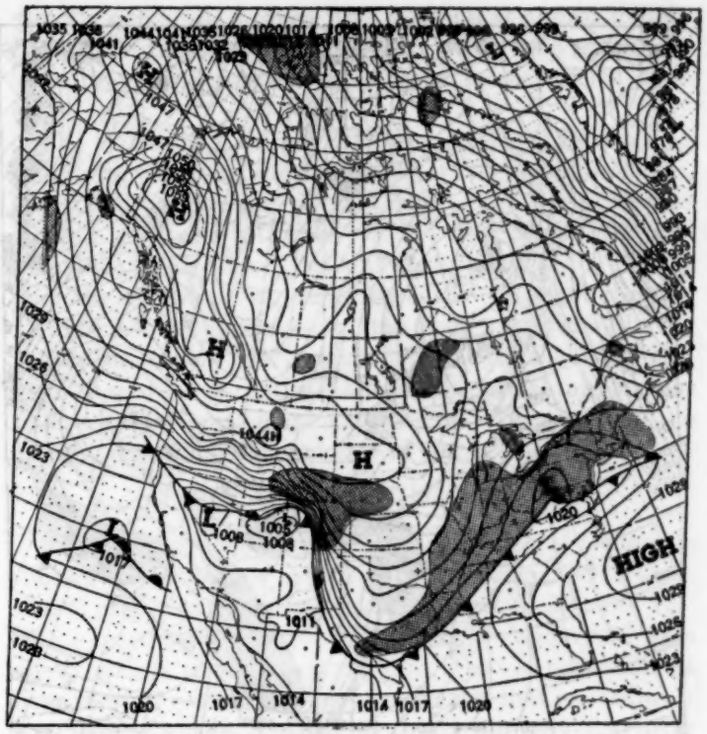

FIGURE 4.—Surface weather chart for 0030 GMT, January 29, 1951.

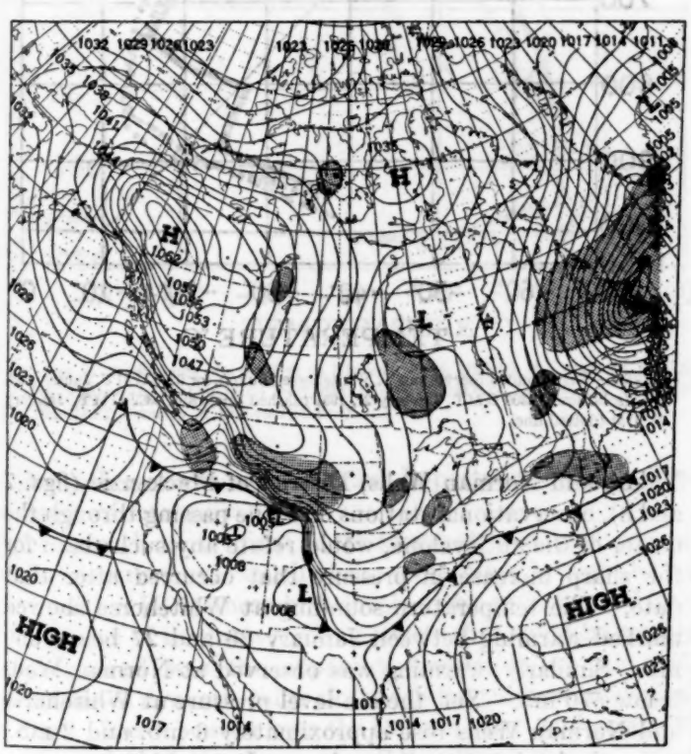

FIGURE 3.—Surface weather chart for 0030 GMT, January 28, 1951.

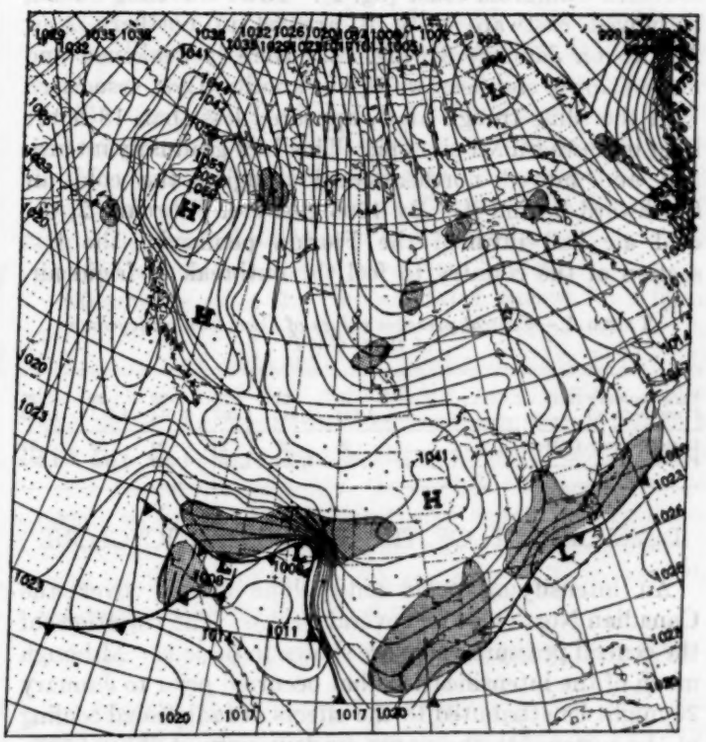

FIGURE 5.—Surface weather chart for 0030 GMT, January 30, 1951.

934723—51——3

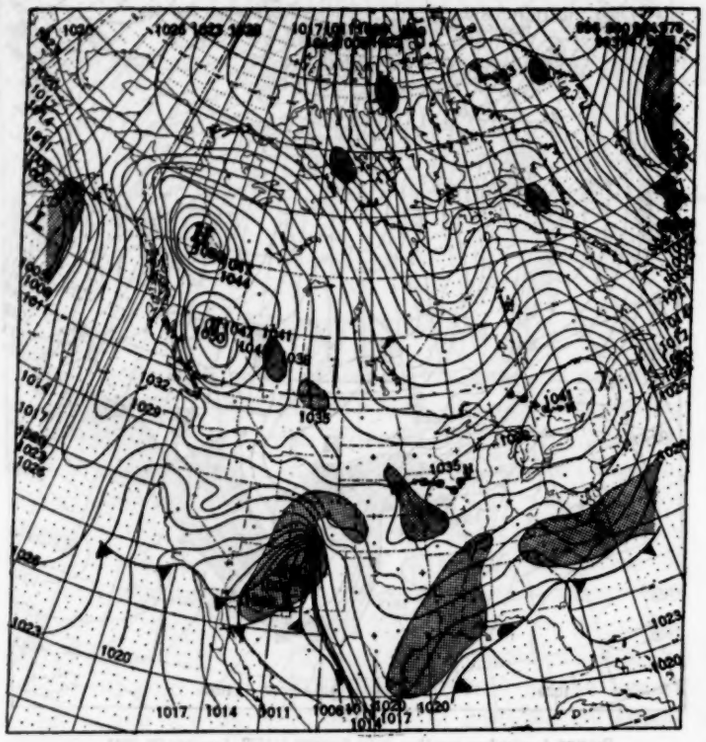

FIGURE 6.—Surface weather chart for 0030 GMT, January 31, 1951. Squares indicate 6-hourly positions of High.

The cyclone that started the final southward plunge of the cold air appeared on January 29, to the west of the southern California coast (fig. 4). After traveling inland, it moved eastward until it arrived in northern New Mexico on January 31 (fig. 6). Here it weakened and moved slowly southeastward, but another Low, associated with the same trough aloft, appeared less than 18 hours later in southern Mississippi. This Low gradually intensified and moved northeastward bringing the cold air southward behind it. By 1200 GMT of February 2, the cold air had invaded the Florida peninsula, the last section of the country to feel the outbreak of frigid air.

TABLE 1.—*Central pressure values of Canadian anticyclone at 0030 GMT*

Date (January 1951)	20	21	22	23	24	25
Pressure (mb.)	1,034	1,042	1,037	1,044	1,053	1,052
Date (January 1951)	26	27	28	29	30	31
Pressure (mb.)	1,051	1,061	1,065	1,060	1,060	1,052

DEVELOPMENT OF THE INTENSE ANTICYCLONE

An intensifying polar anticyclone existed over the Canadian Northwest for several weeks. The variations of the central pressure value are shown in table 1. Although much of the intensification that occurred prior to January 26 might be attributed to the effects of radiational cooling at the surface [4], the upper-air soundings at Whitehorse,

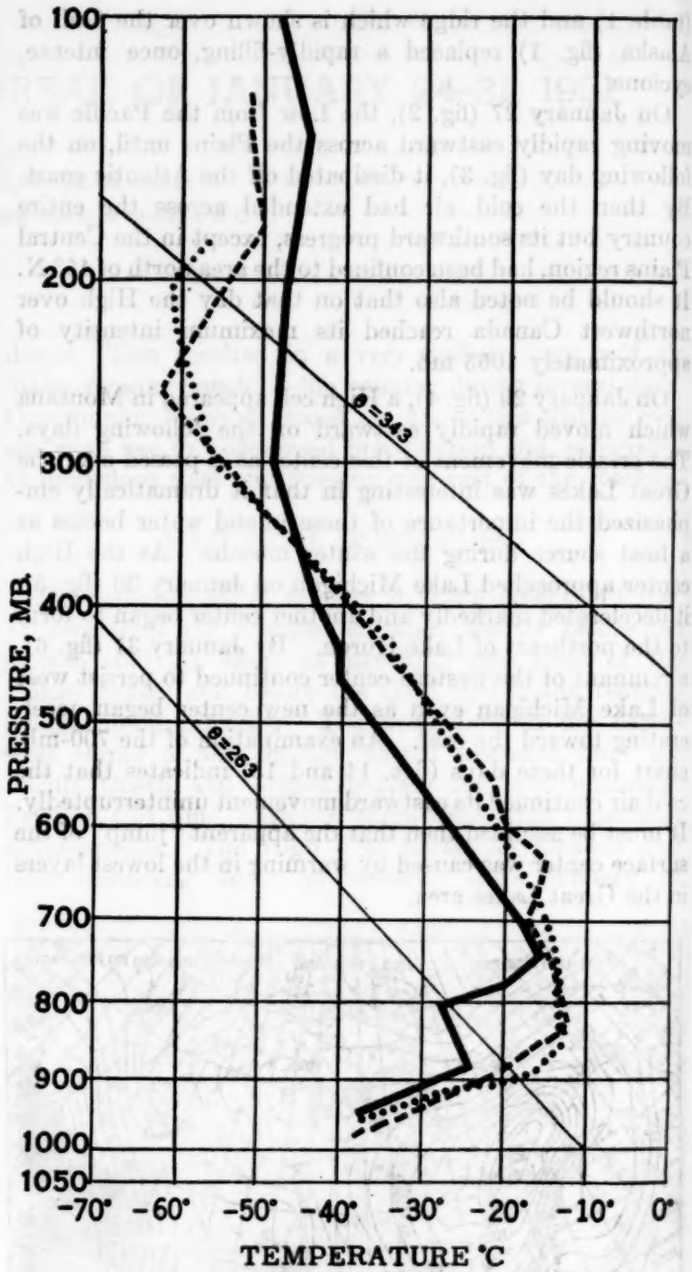

FIGURE 7.—Radiosonde observations at Whitehorse, Yukon, for 0300 GMT, January 26, 1951 (solid line); 0300 GMT, January 27, 1951 (dashed line); and 0300 GMT, January 28, 1951 (dotted line).

Yukon and Norman Wells, District of Mackenzie (figs. 7 and 8), observational stations on a line passing through the center of the anticyclone, would refute any such claim for the sharp increase in pressure that occurred after that date. The temperature sounding at Whitehorse showed marked warming between January 26 and 27 below 360 mb. Similarly, warming was observed at Norman Wells below 570 mb. Yet, the sea level pressure at Whitehorse and Norman Wells rose approximately 6 mb. and 2 mb., respectively, between these days. It would thus appear

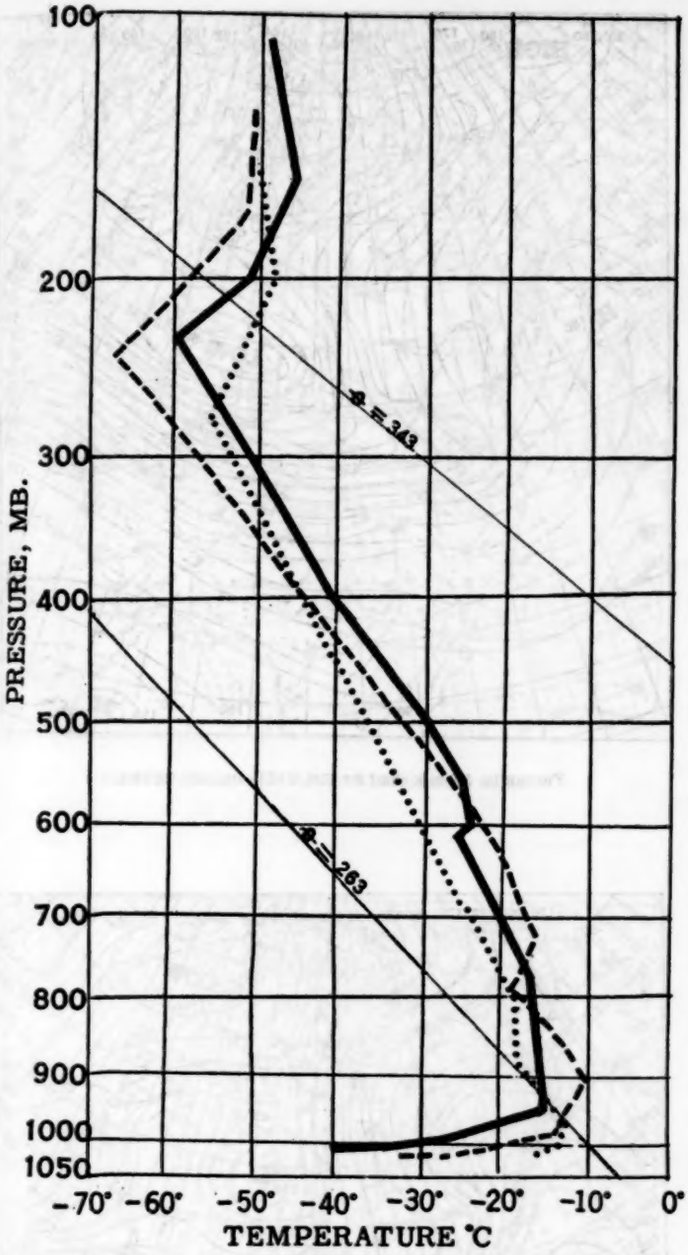

FIGURE 8.—Radiosonde observations at Norman Wells, District of Mackenzie, for 0300 GMT, January 26, 1951 (solid line); 0300 GMT, January 27, 1951 (dashed line); and 0300 GMT, January 28, 1951 (dotted line).

that other effects were of prime importance in these final stages of intensification.

One such cause might be the strong stratospheric cooling that occurred over much of the area, either brought on by advection [5] at these high levels or by radiation. However, one of the most striking effects that could be readily ascertained was the apparent association of the well-developed dynamic ridge aloft with the surface intensification. It can be seen from the 500-mb. chart of January 27 (fig. 10) that there was a well-developed "warm" ridge directly above the surface High position at approximately the time of the maximum intensity. This is in agreement with previous observations of very intense polar anticyclones [5].

The warm ridge at this level first appeared as a strong "blocking" High to the southwest of the Aleutian Chain. It gradually intensified northward into the Bering Straits where a separate cell broke off. It then proceeded eastward over the Beaufort Sea and finally southward, passing over the northwest corner of Canada. Figures 9 through 12 illustrate the movement of the High at 500 mb. during the latter part of the trajectory. It will be noted also from these figures that great warming at 500 mb. accompanied the migration, particularly in the center of the High and on the left-hand side of the path of movement.

TRAJECTORY OF THE COLD AIR

The unusual trajectory of the cold air out of Canada is illustrated by the flow patterns that existed on the 700-mb. charts of the days under discussion (figs. 13, 14, and 15). The important features of the pattern of January 26 were the extensive, strong, northerly flow that was predominant over most of central Canada, the trough that existed over southwest Canada, and the generally westerly flow over the entire United States. The events which led to this pattern included the following: The ridge development over northwest Canada increased the northerly flow to the east of it. At the same time a ridge was intensifying about 400 miles off the northwest coast. Between these two regions the cold trough in southwest Canada intensified.

The cold air in the trough originated in northern Alaska, having been advected southward around an intense Low over the Gulf of Alaska. Eventually the Low became a "cold" type and filled, but not before a remnant of it, accompanied by a core of cold air, moved inland. This initial surge from the Pacific was later reinforced by a tongue of cold air from central Canada. On January 26 (fig. 13), the cold air is seen to be moving southeastward out of Canada into the northwestern States.

Meanwhile, over the United States, except for a filling trough along the east coast, the wave amplitude of the westerlies was quite small. Thus by January 28 (fig. 14), the cold air that had entered the northwestern States had swept rapidly across the northern tier of States at 700 mb. evidencing very slight southward displacement.

On January 30 (fig. 15), the trough changed its orientation to northeast-southwest and began to accelerate. When that occurred the cold air was then advected southward to the rear of the trough and eventually covered the southern extremities of the country.

EFFECTS ON WEATHER OVER THE UNITED STATES

A concept of the amount of subsidence that took place east of the Rockies within the cold air may be had from

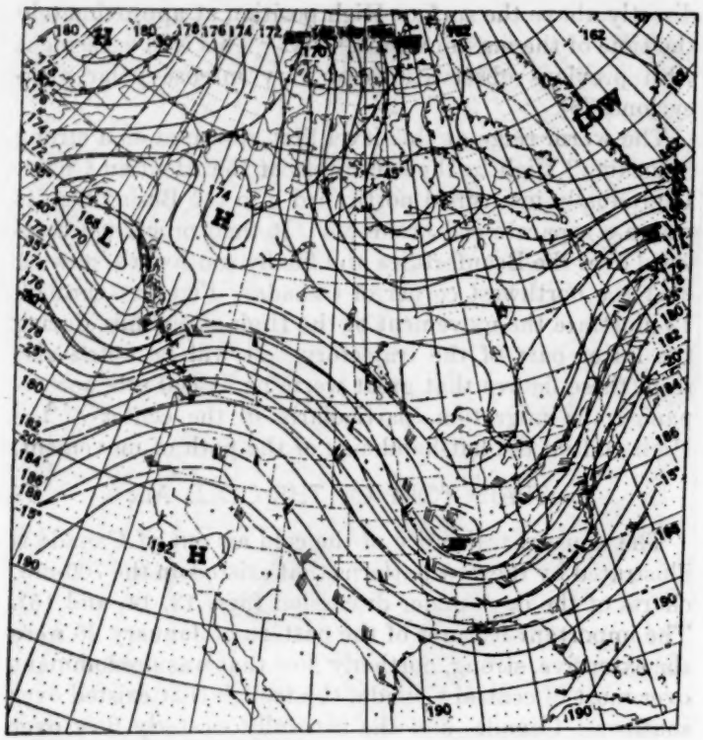

FIGURE 9.—500-mb. chart for 0300 GMT, January 25, 1951. Contours (solid lines) at 200-ft. intervals are labeled in hundreds of geopotential feet. Isotherms (dashed lines) are at intervals of 5° C. Barbs on wind shafts are for speeds in knots (pennant=50 knots, full barb=10 knots, and half-barb=5 knots).

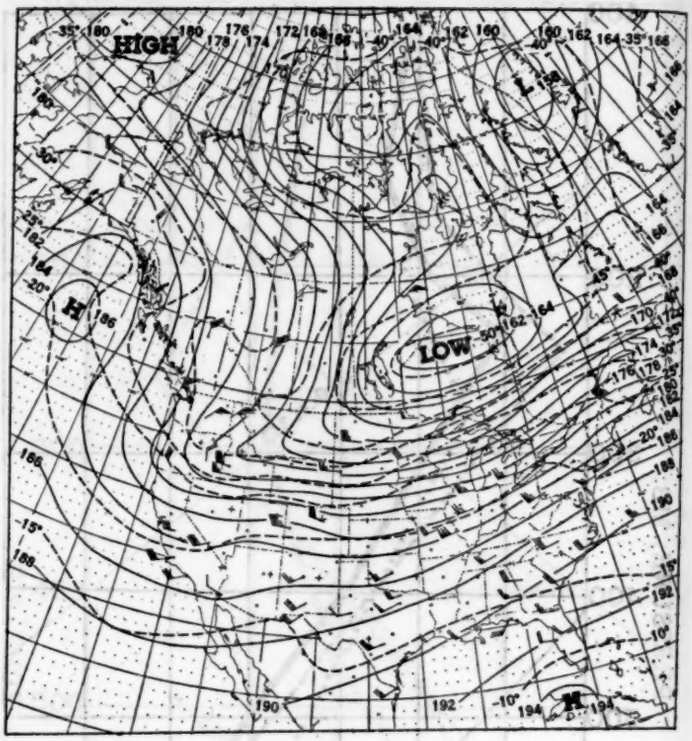

FIGURE 11. 500-mb. chart for 0300 GMT, January 29, 1951.

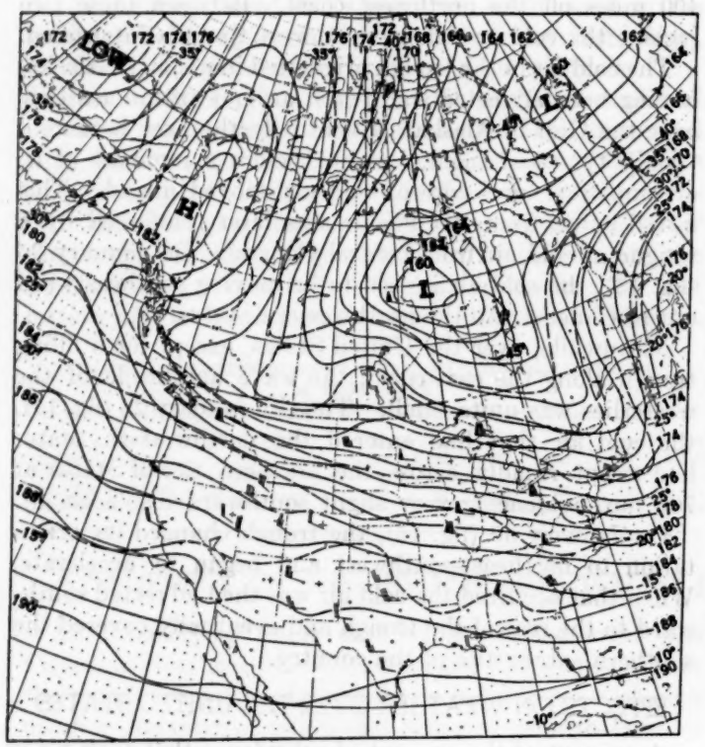

FIGURE 10.—500-mb. chart for 0300 GMT, January 27, 1951.

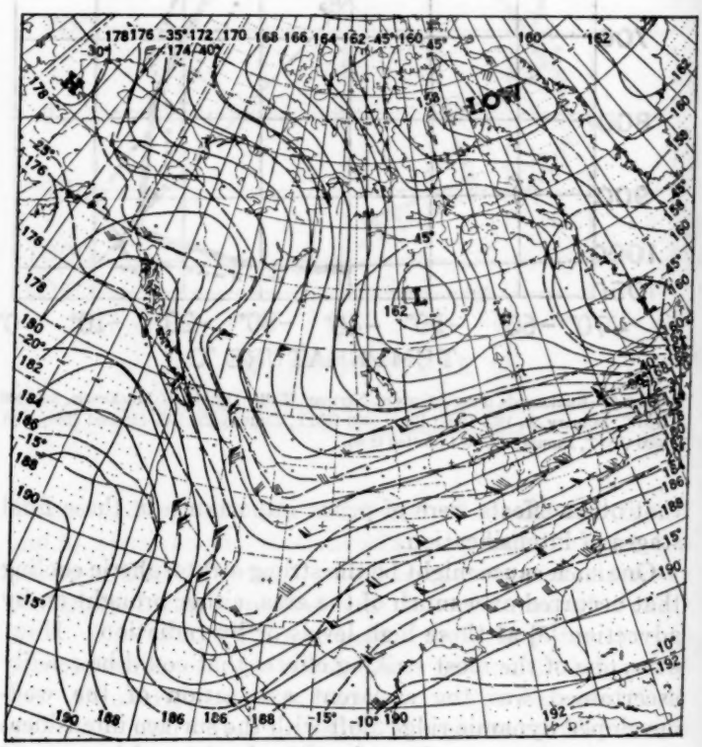

FIGURE 12.—500-mb. chart for 0300 GMT, January 31, 1951.

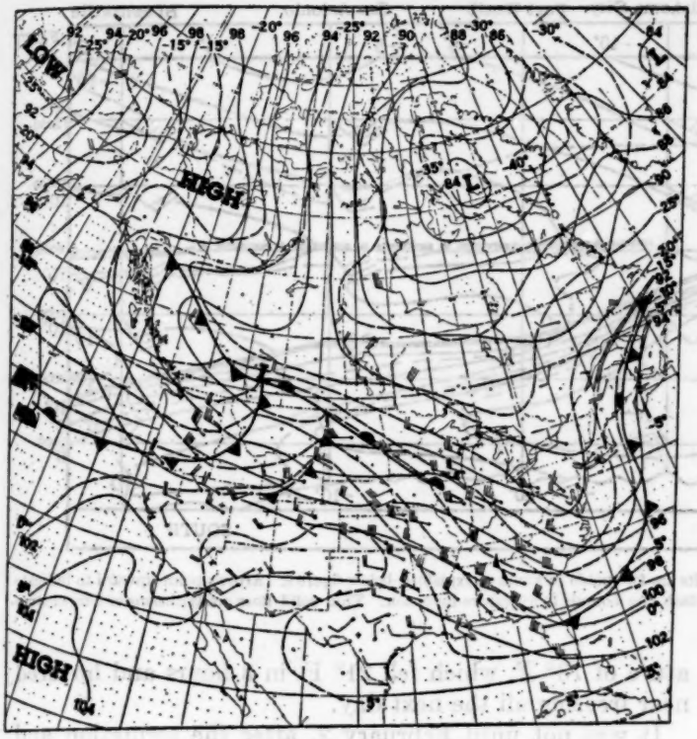

FIGURE 13.—700-mb. chart for 1500 GMT, January 26, 1951.

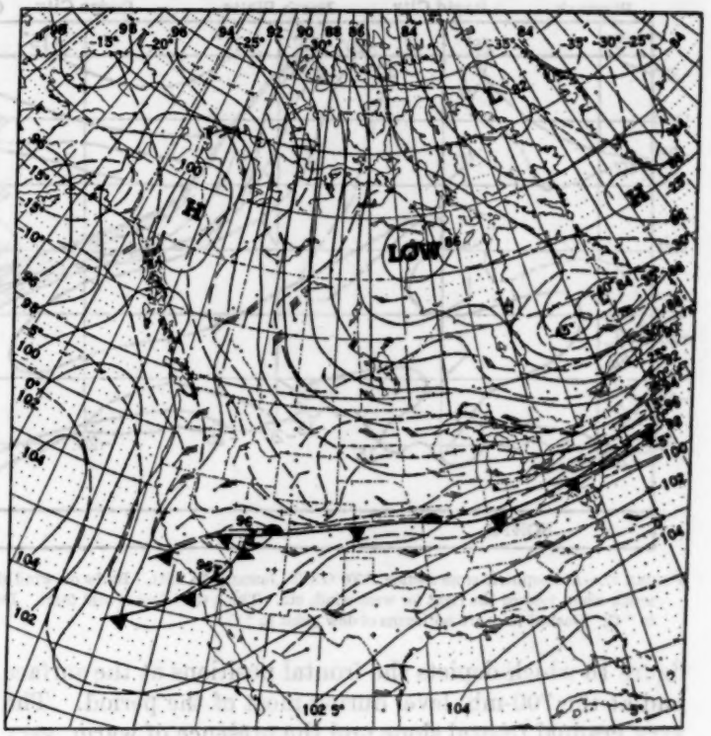

FIGURE 15.—700-mb. chart for 1500 GMT, January 30, 1951.

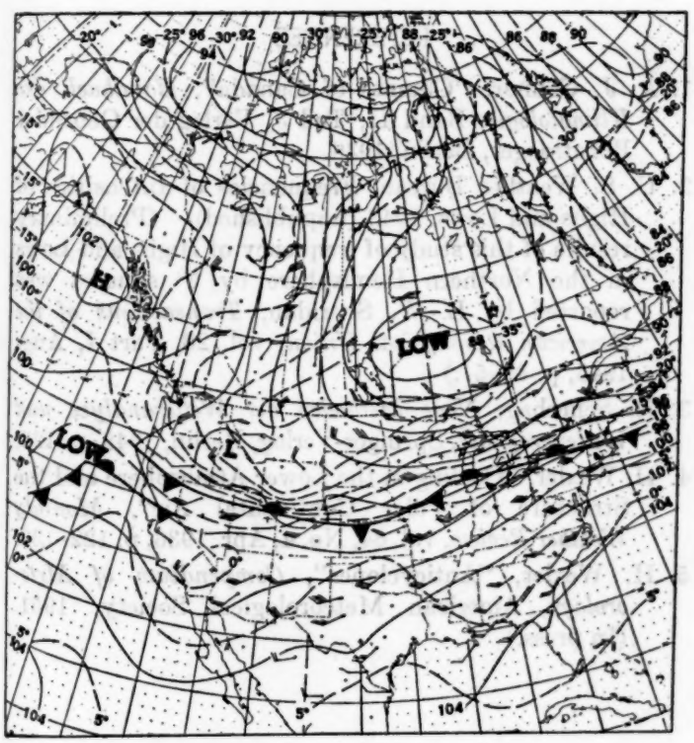

FIGURE 14.—700-mb. chart for 1500 GMT, January 28, 1951.

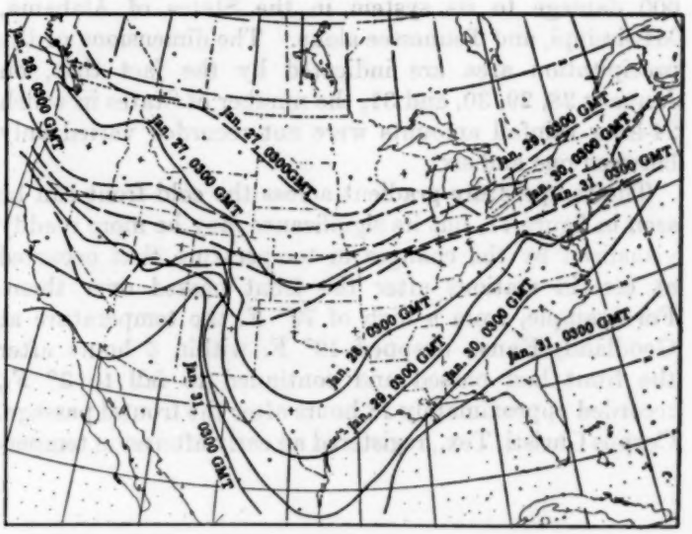

FIGURE 16.—Frontal positions at the surface and 700-mb. levels. Solid lines represent surface positions, dashed lines 700-mb. positions.

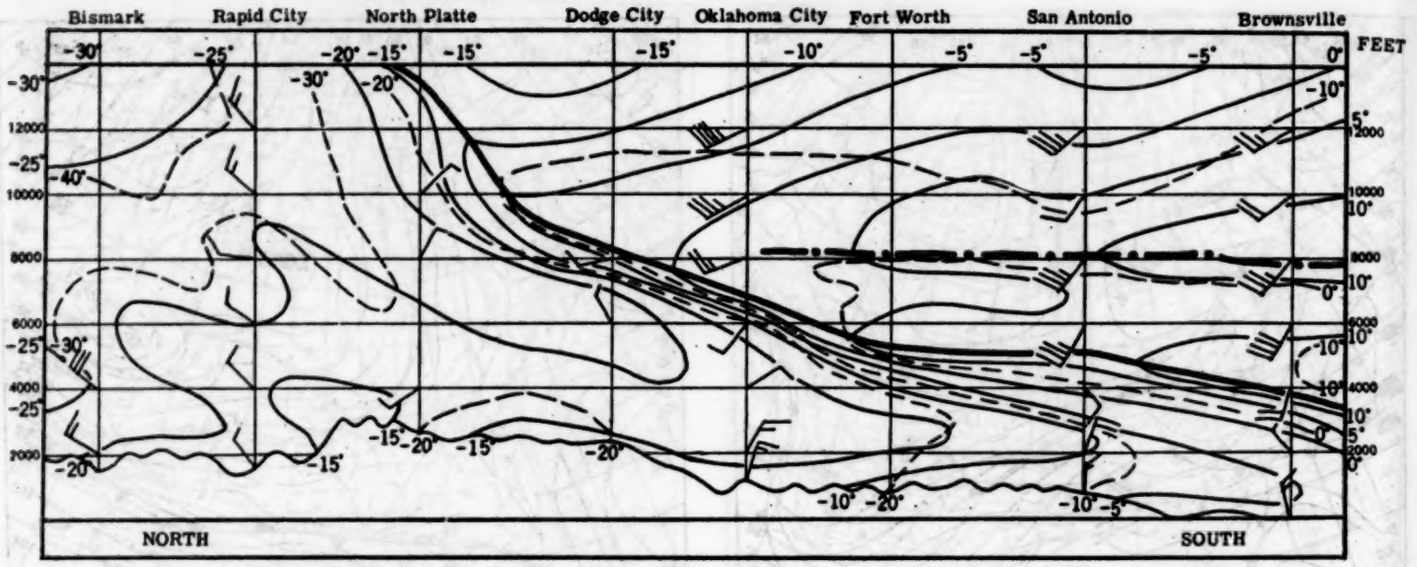

FIGURE 17.—Atmospheric cross section, 1500 GMT, January 30, 1951. Barbs on wind shafts are for speeds in knots as explained below figure 9. Arrows point upward to indicate south wind, toward the right for west wind, etc. Thick solid line is cold front. Dot-dash line bounds temperature inversion. Thin solid lines are isotherms of temperature in ° C. Dashed lines are isotherms of dew point in ° C.

figure 16 which depicts the frontal positions at the surface and at the 700-mb. level during most of the period. The very gradual frontal slope and the presence of warm, very humid air riding above it is illustrated by the vertical atmospheric cross section of figure 17. The latter illustration typifies conditions that existed over the entire eastern half of the country during the last few days of the month.

Sleet and freezing rain were not only severe in many places but covered large areas, resulting in widespread damage. For example, the Telephone Company reported that disruption to its service, particularly in the southern States, was the most extensive in its history, with $8,000,000 damage to its system in the States of Alabama, Mississippi, and Tennessee alone. The dimensions of the precipitation area are indicated by the fact that, on January 28, 29, 30, and 31, the number of States in which 24-hour rainfall amounts were not recorded varied only between one and six.

The temperature gradient across the cold front can be seen in figure 17, but its significance may be more readily visualized by the changes in temperature that occurred at certain stations after the front passed over them. For example, from a high of 79° F. the temperature at Goodland, Kans., dropped 49° F. within 6 hours after the front had passed and continued to fall to 3° F., recorded approximately 18 hours after the frontal passage. Corpus Christi, Tex., registered an early afternoon temperature of 73° F. which fell 21° F. in 3 hours and hovered near freezing all the next day.

It was not until February 2, after the formation and rapid movement northeastward of a deep cyclone along the east coast had deepened the cold air and eliminated the extensive overrunning of warm air, that the weather began to clear.

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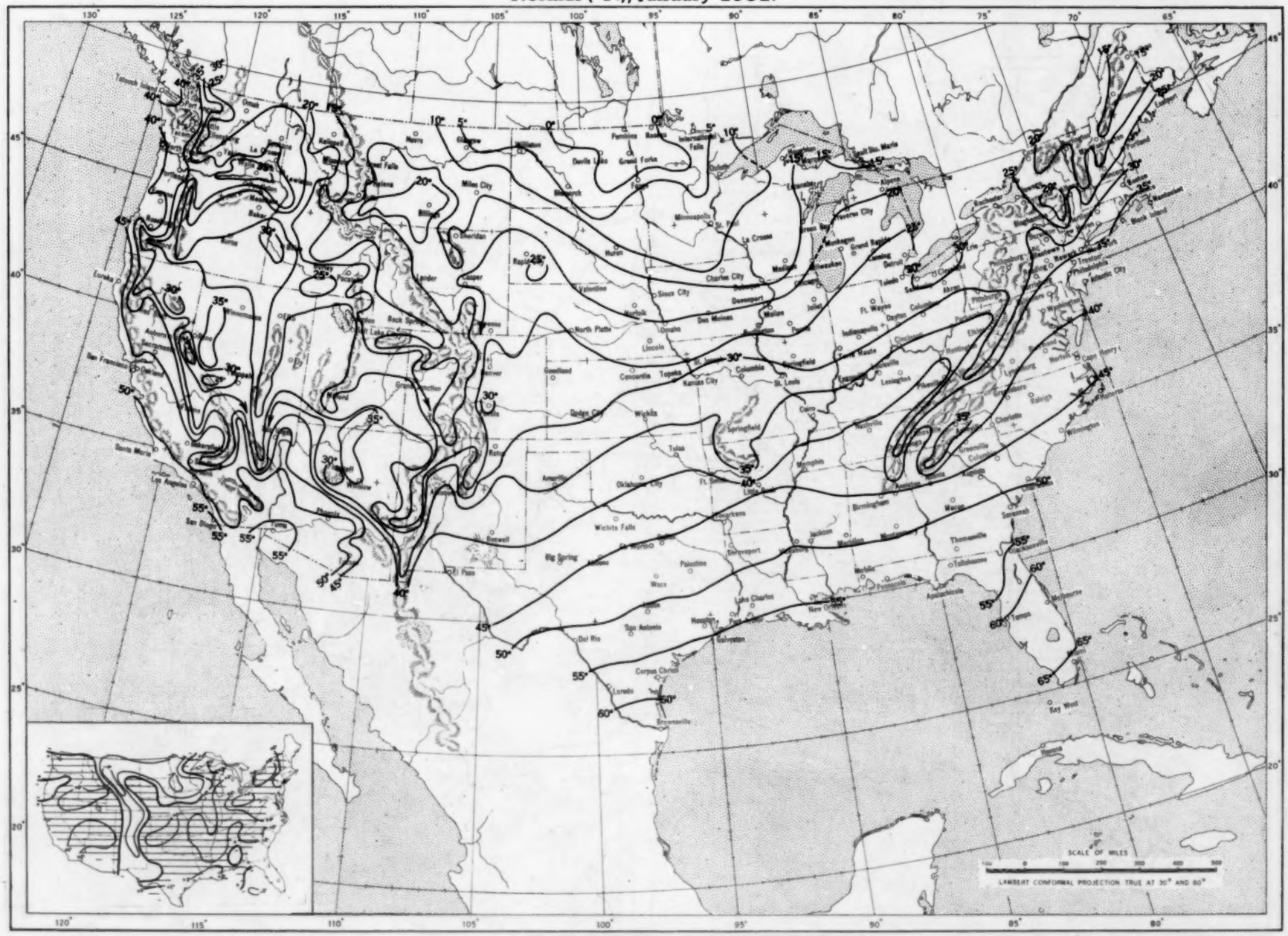
5. H. Wexler, "Anticyclones", *Compendium of Meteorology*, American Meteorological Society, 1951. (In press.)

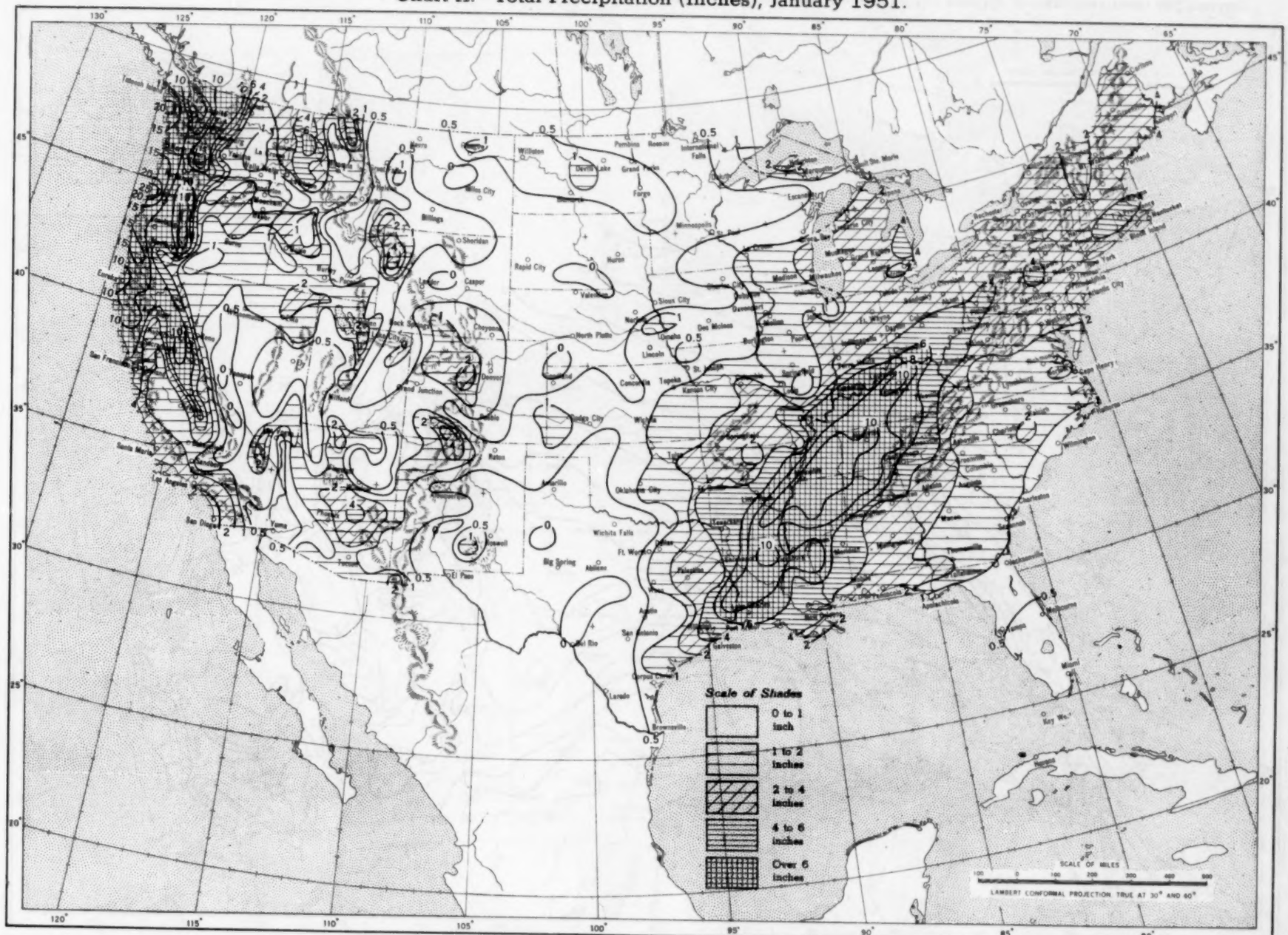
U. S. GOVERNMENT PRINTING OFFICE: 1951

Chart I. Average Temperature (°F.) at Surface, January 1951. Inset: Departure of Average Temperature from Normal (°F.), January 1951.



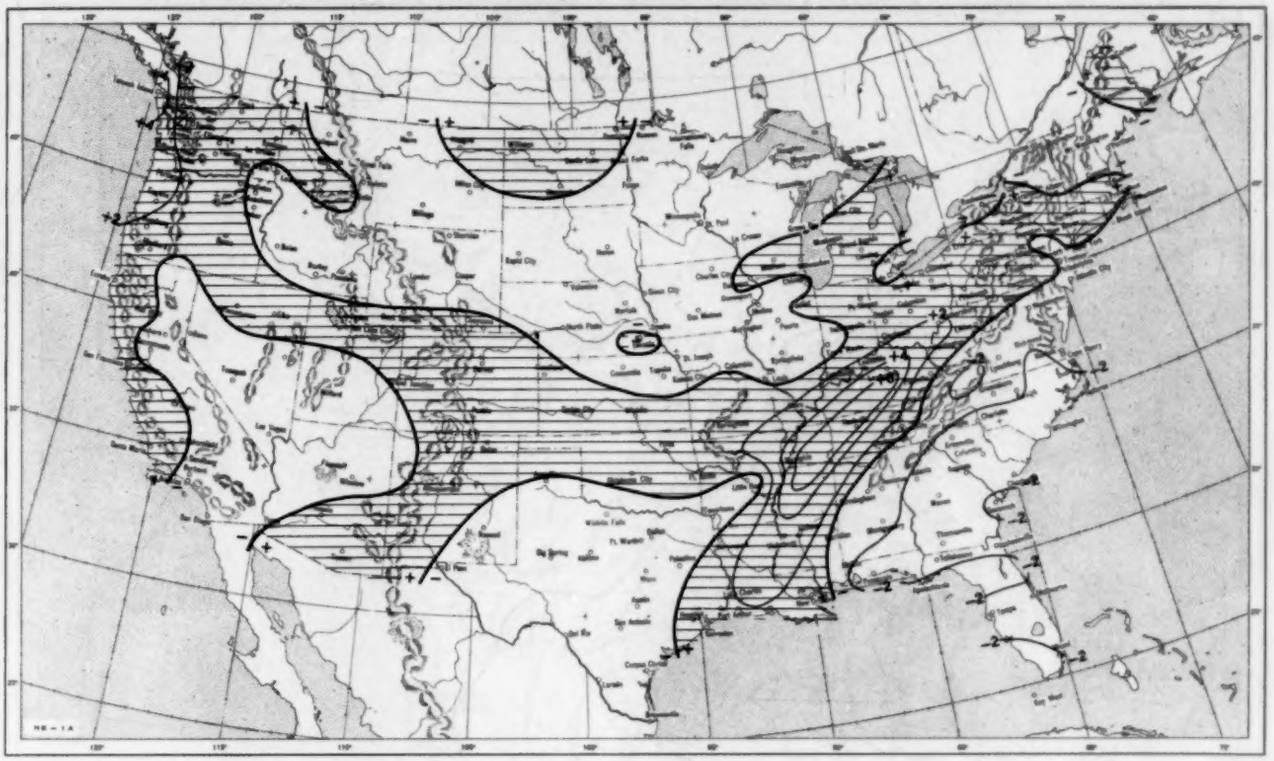
Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), January 1951.

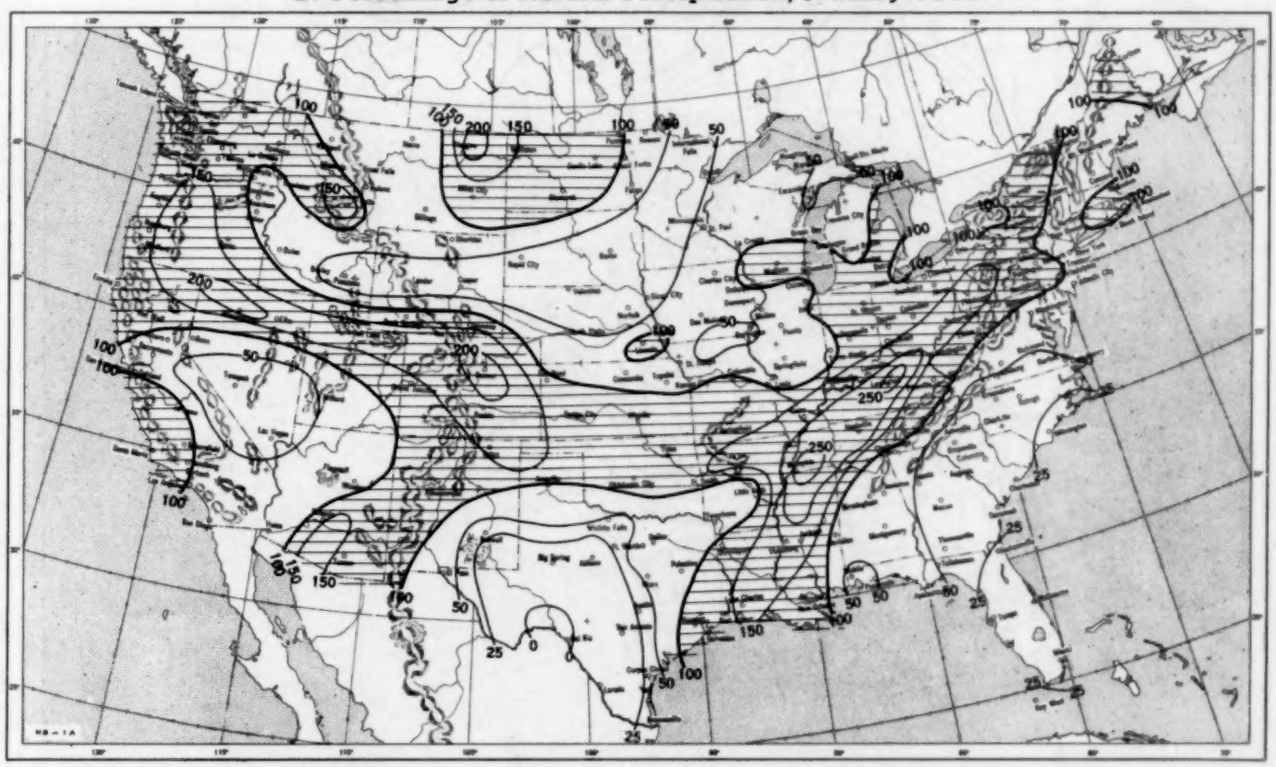

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), January 1951.

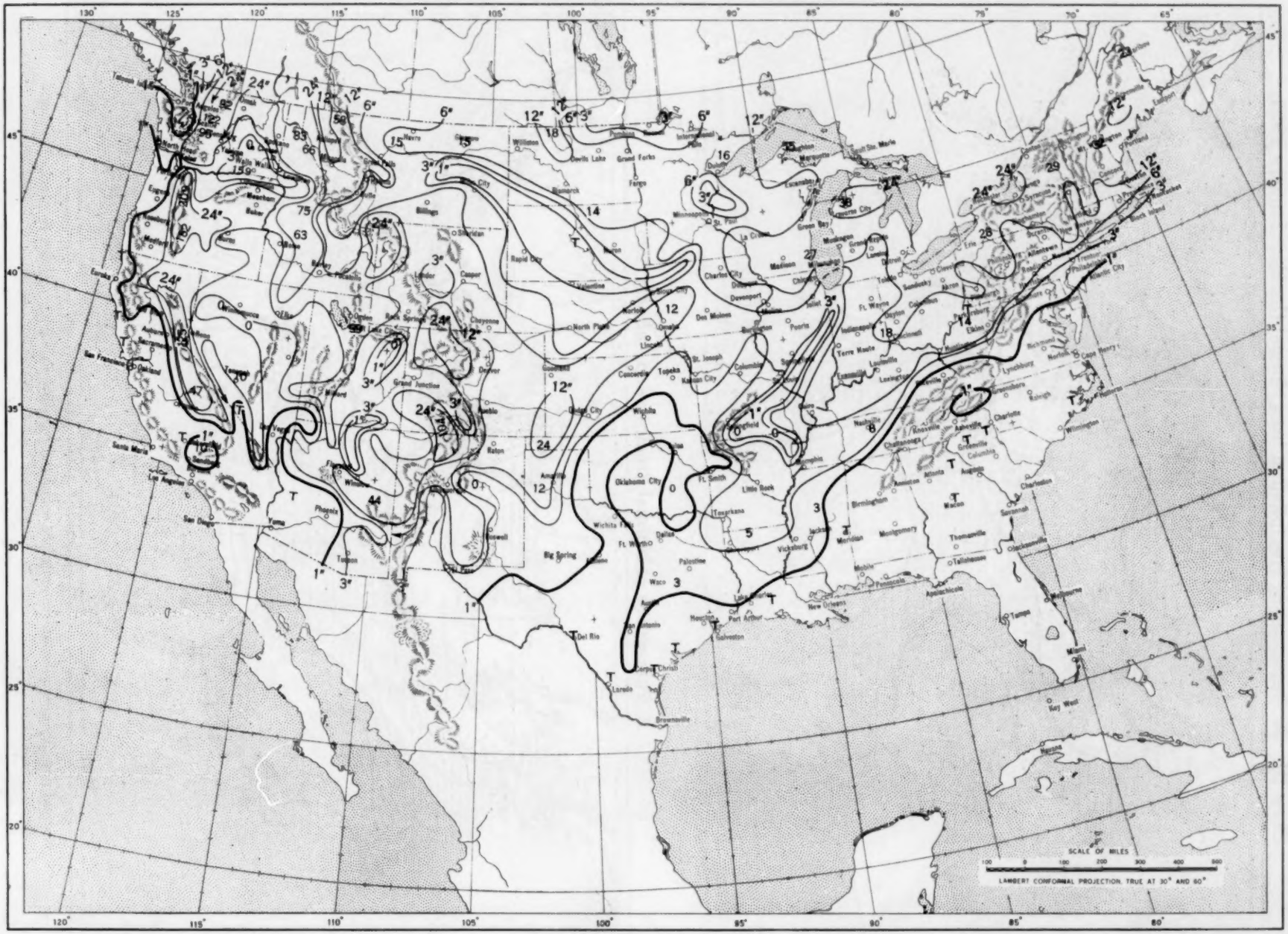


B. Percentage of Normal Precipitation, January 1951.



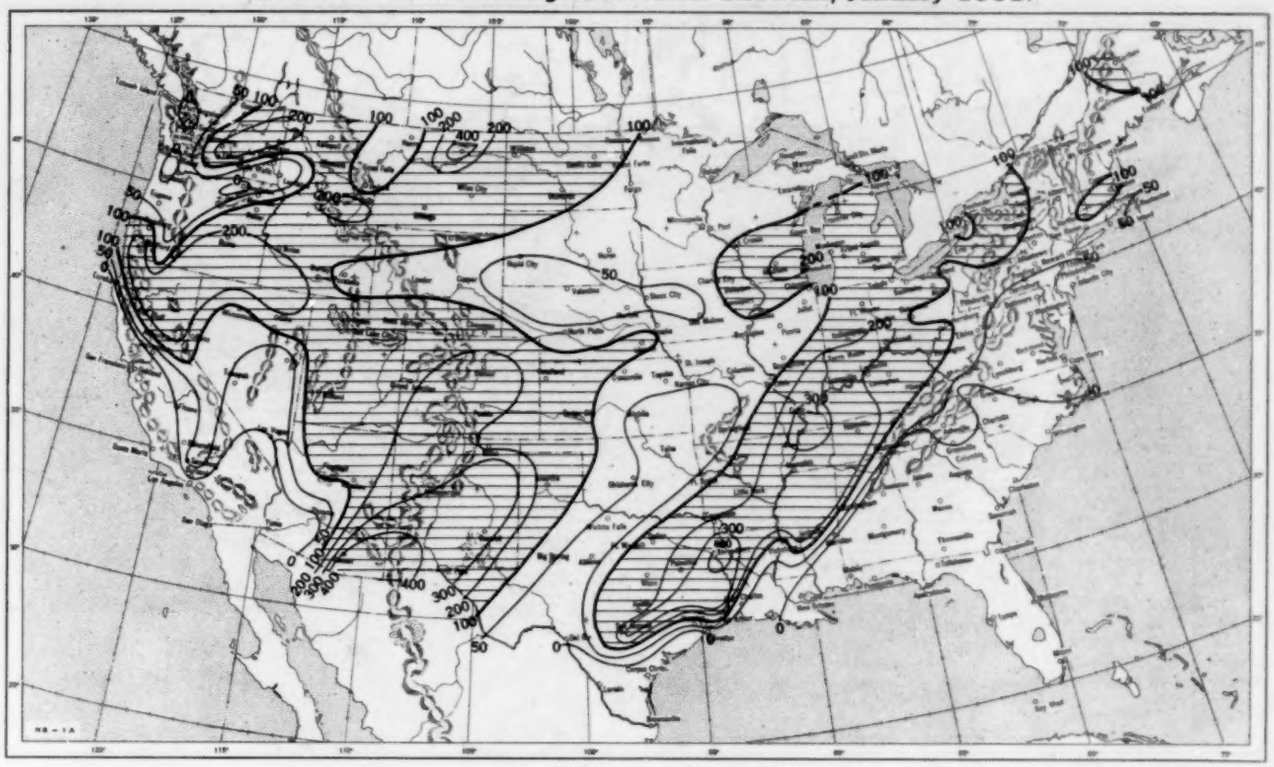
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), January 1951.

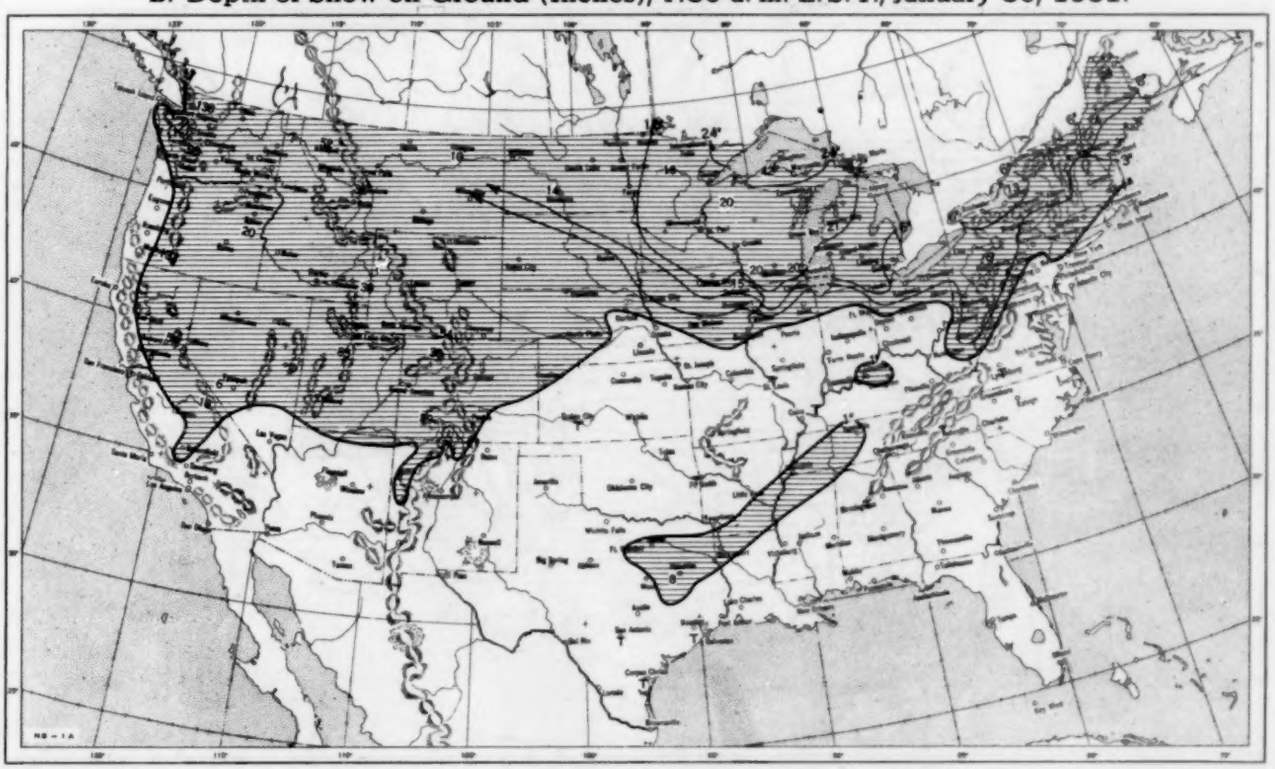


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, January 1951.

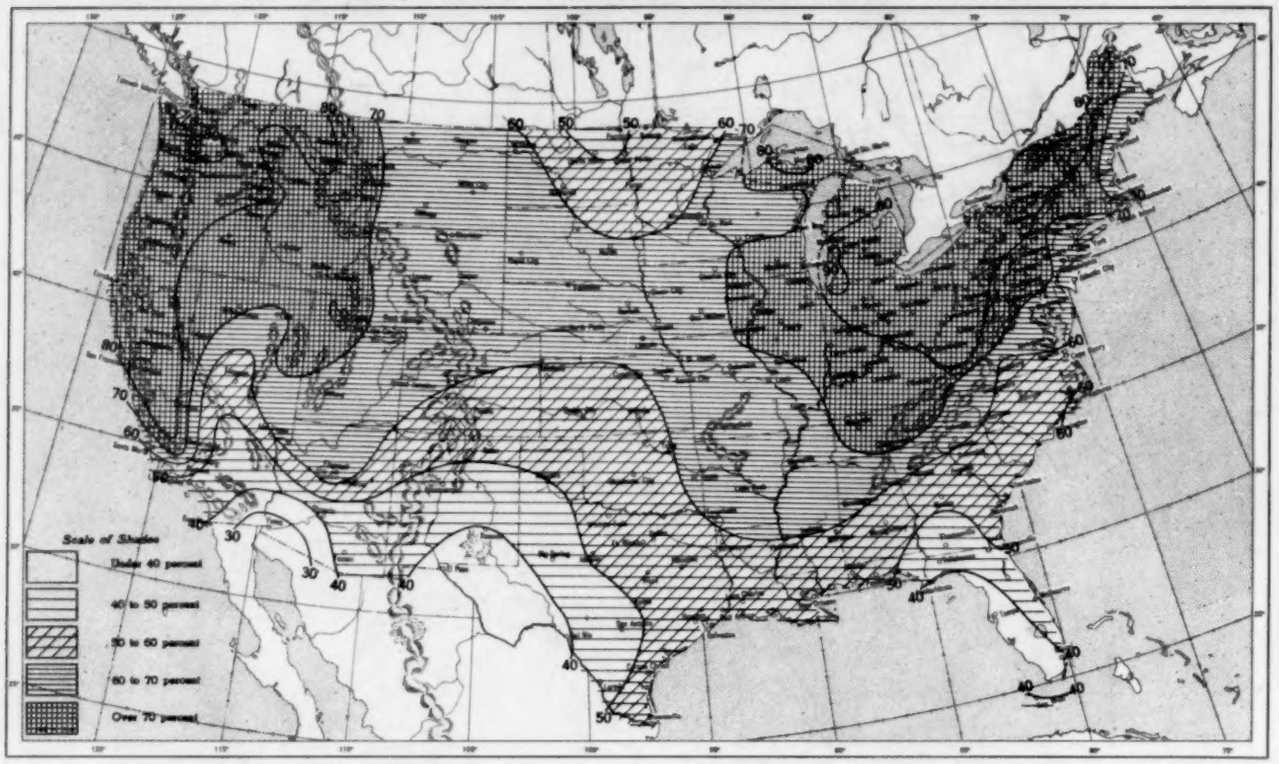


B. Depth of Snow on Ground (Inches), 7:30 a. m. E.S.T., January 30, 1951.

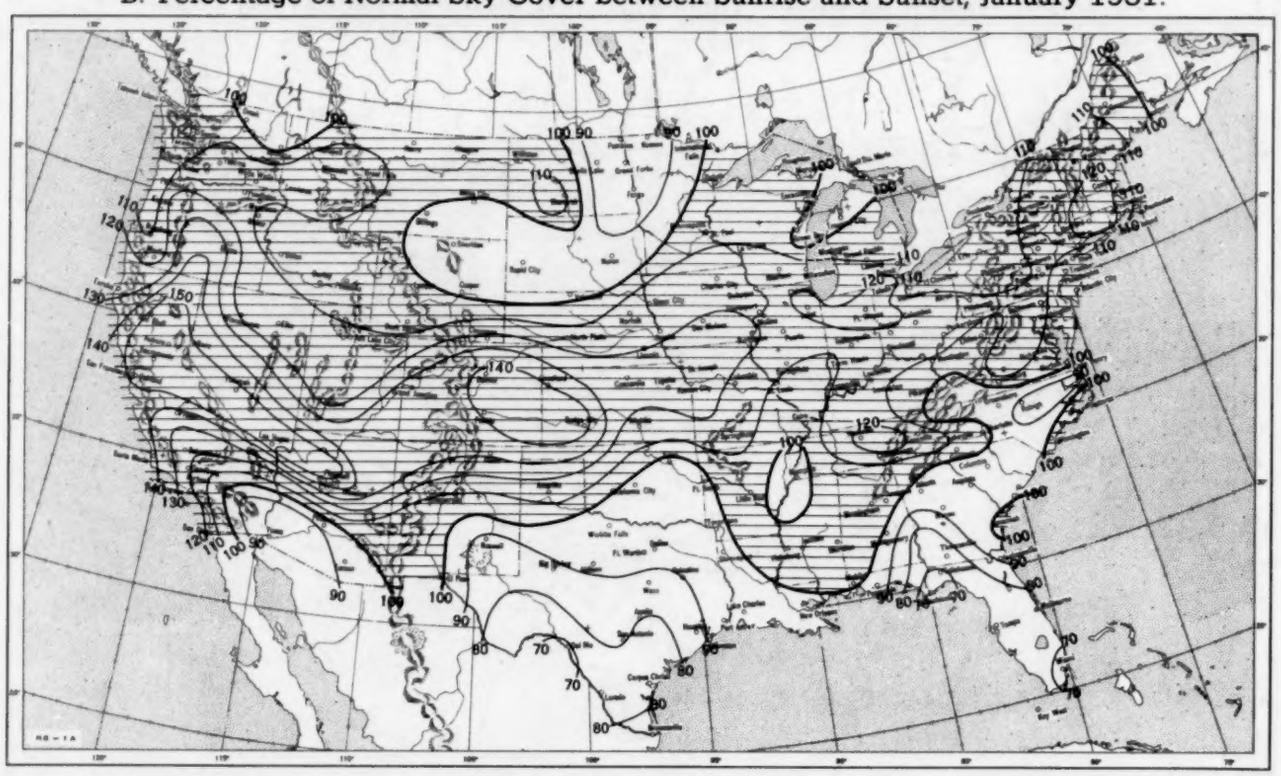


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record. B. shows depth currently on ground at 7:30 a.m. E.S.T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, January 1951.

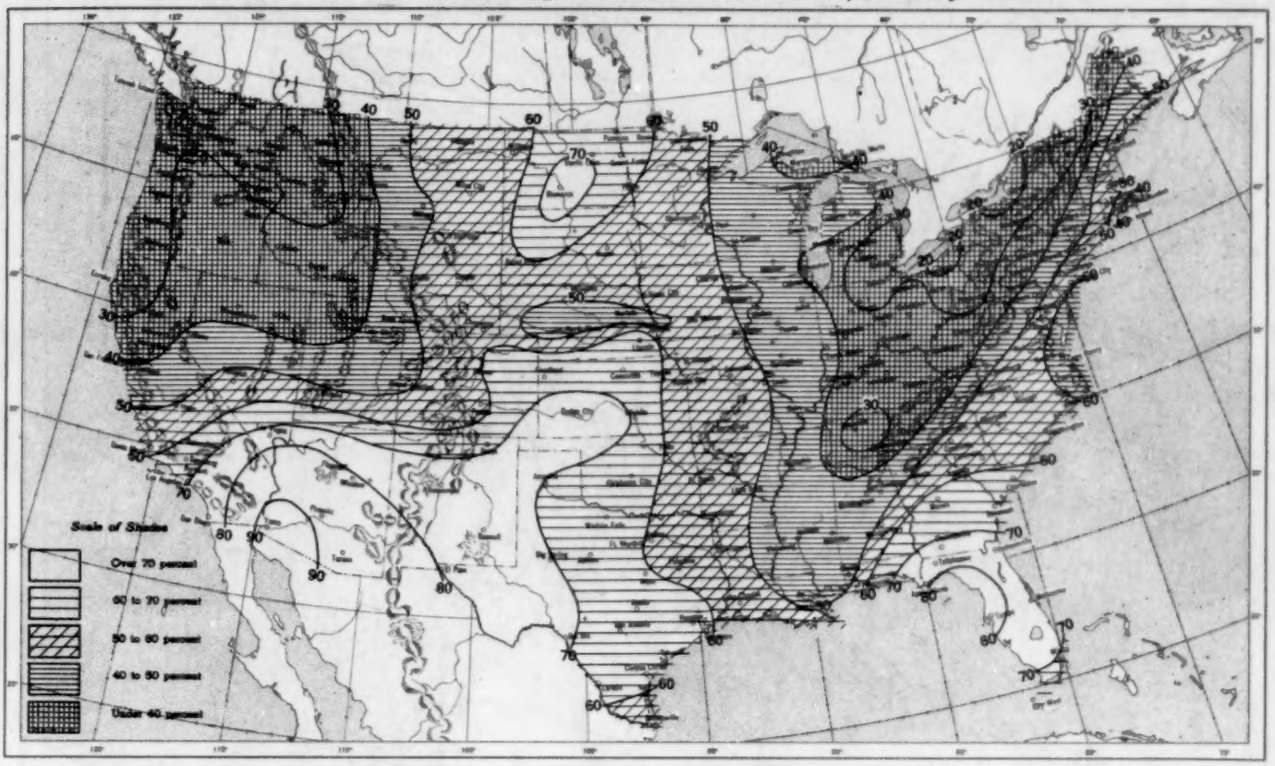


B. Percentage of Normal Sky Cover between Sunrise and Sunset, January 1951.

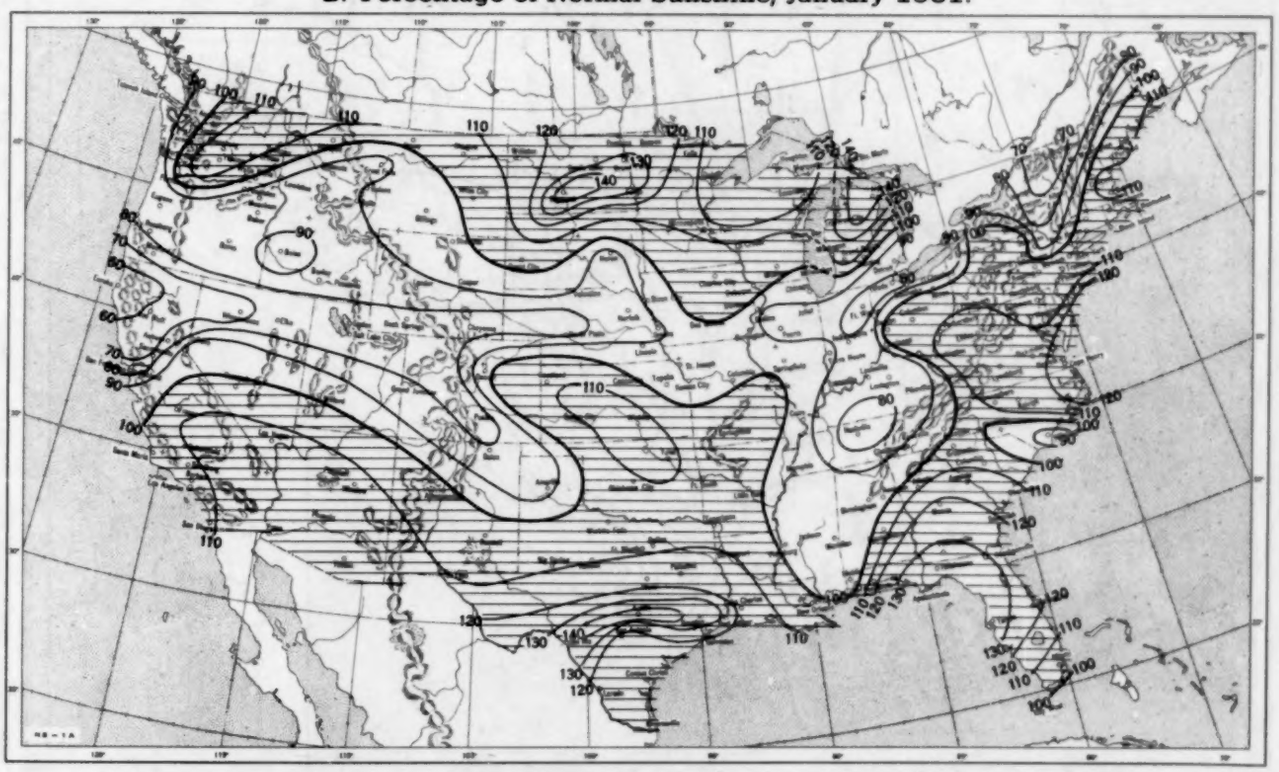


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, January 1951.



B. Percentage of Normal Sunshine, January 1951.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, January 1951. Inset: Percentage of Normal Average Daily Solar Radiation, January 1951.

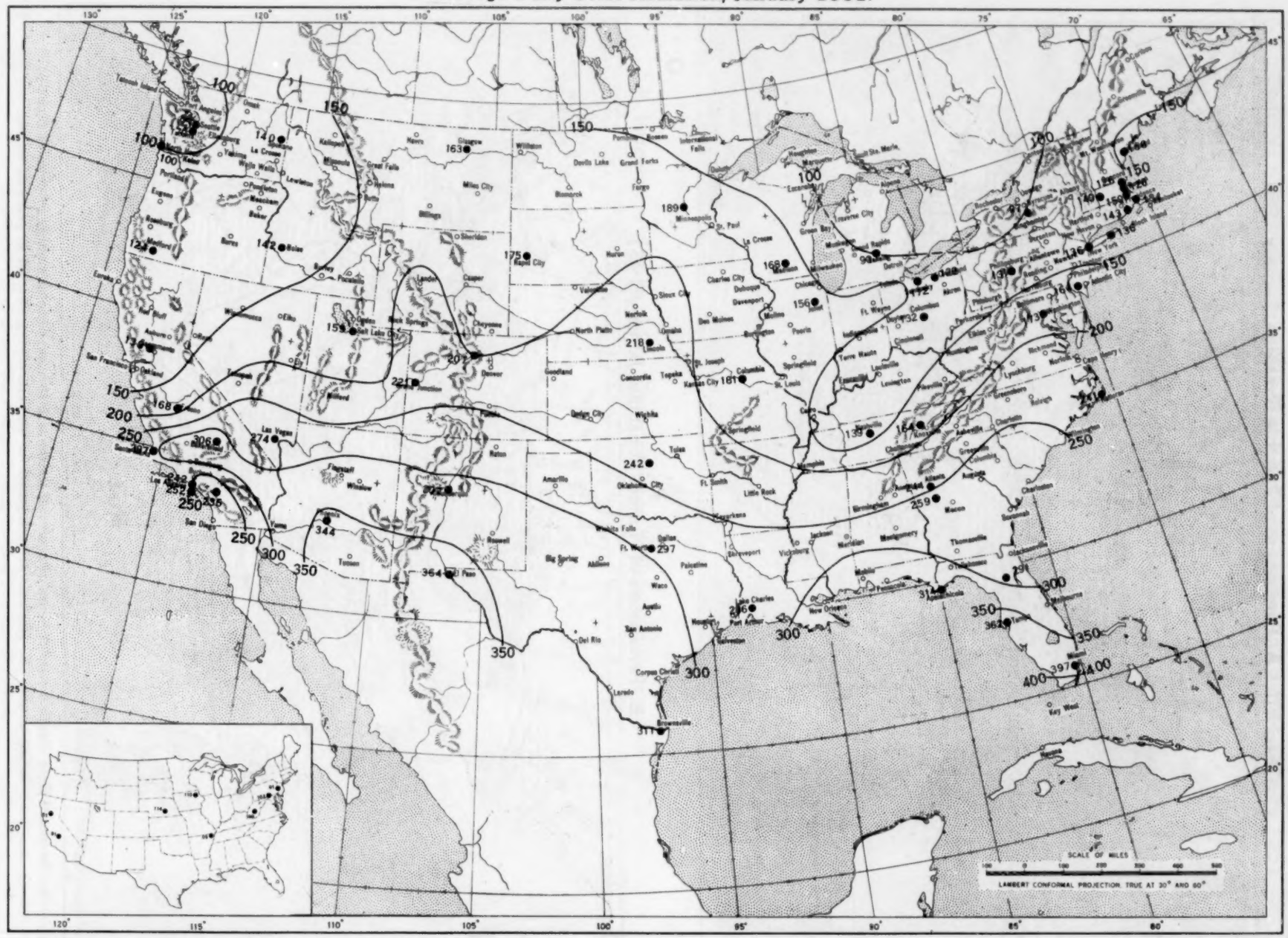
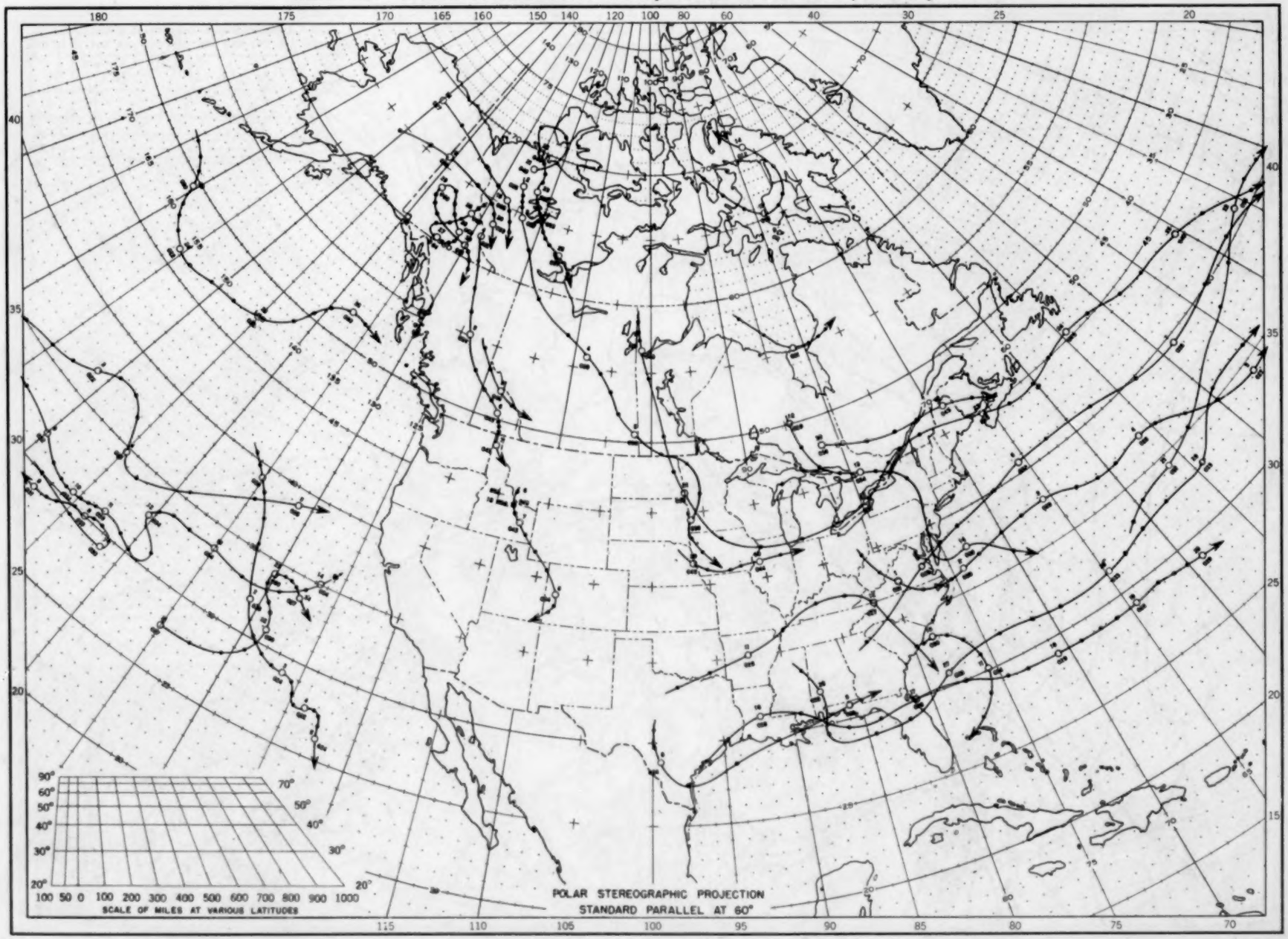


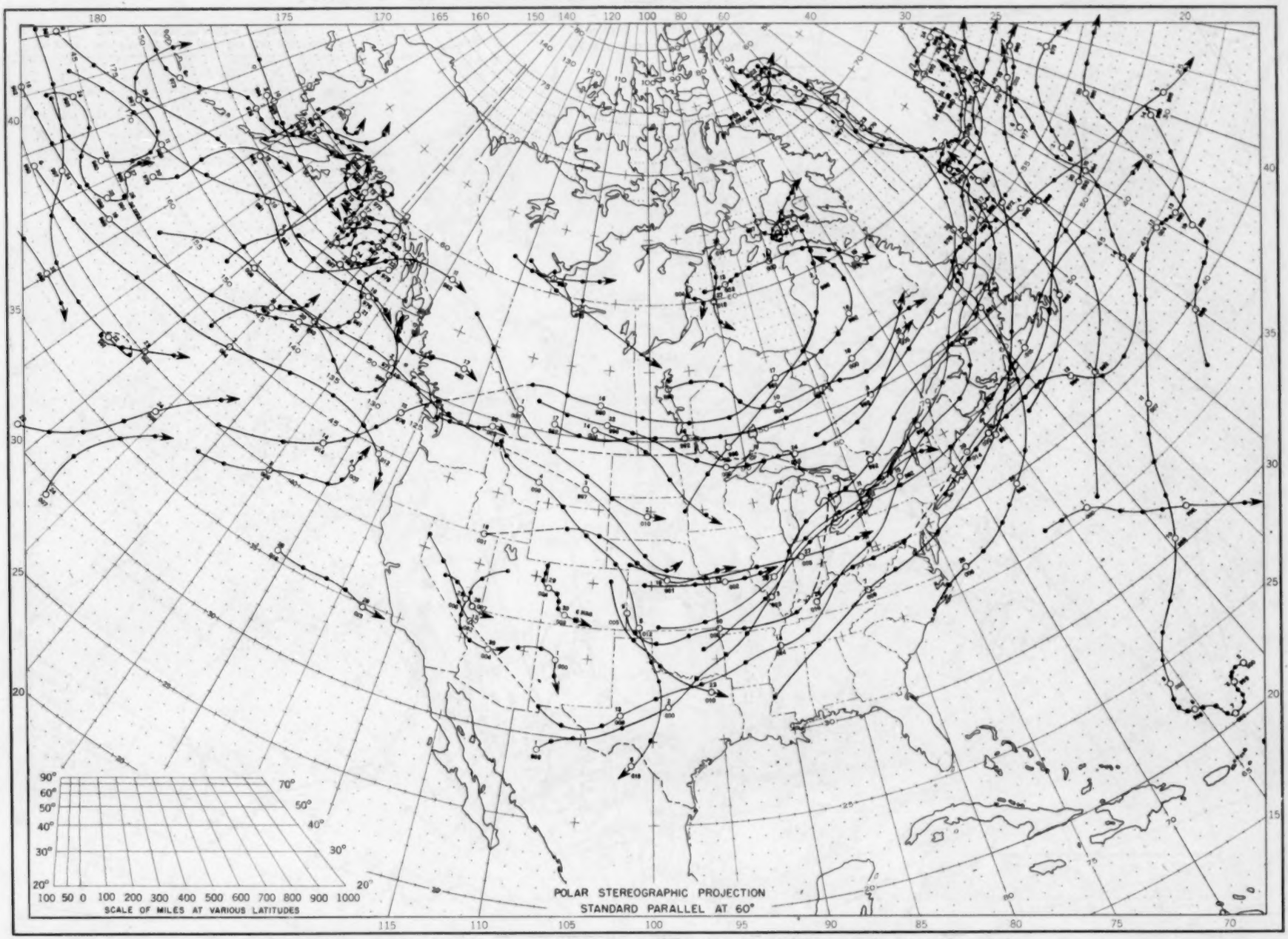
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, January 1951


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000

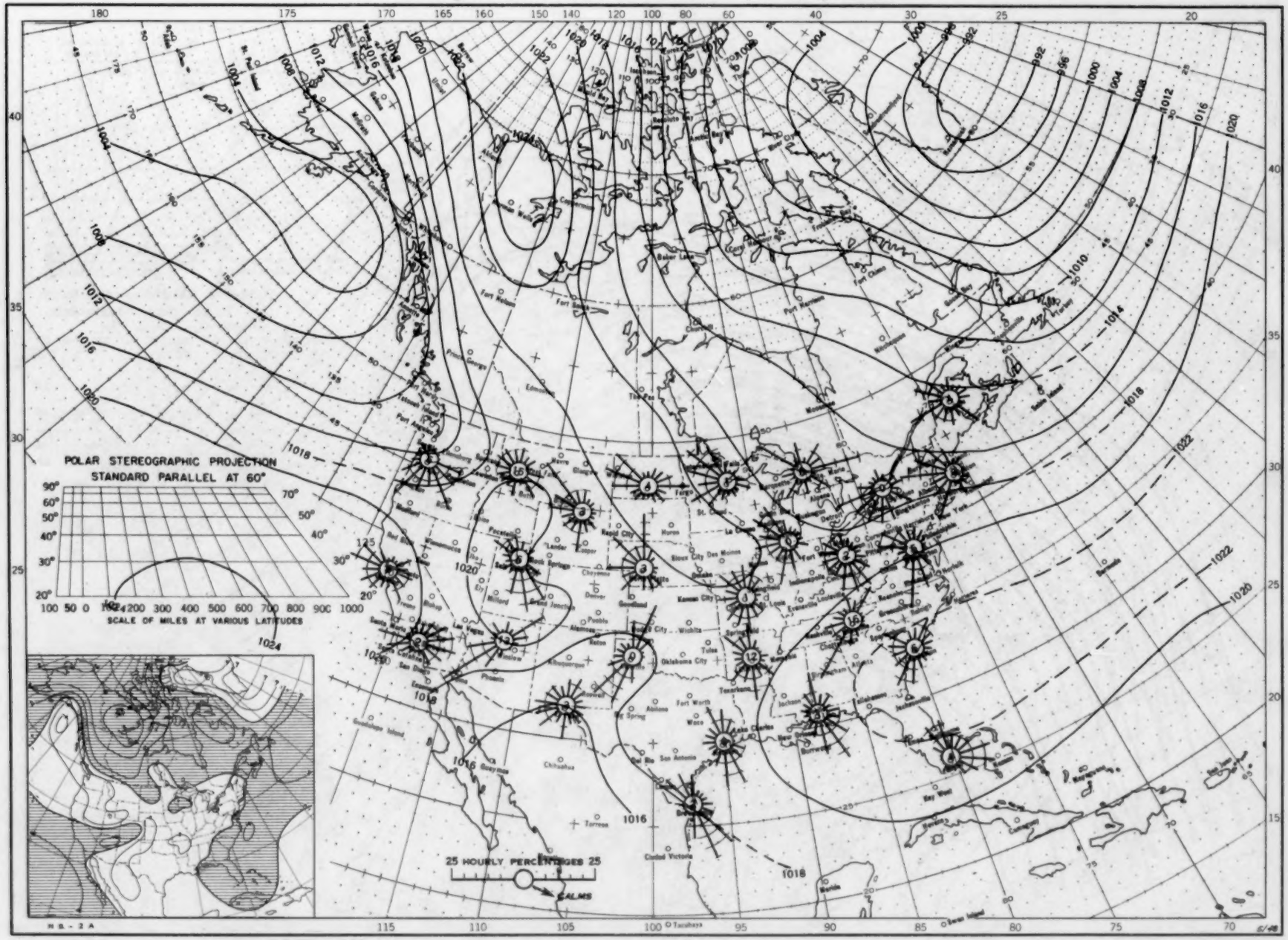
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, January, 1951.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000

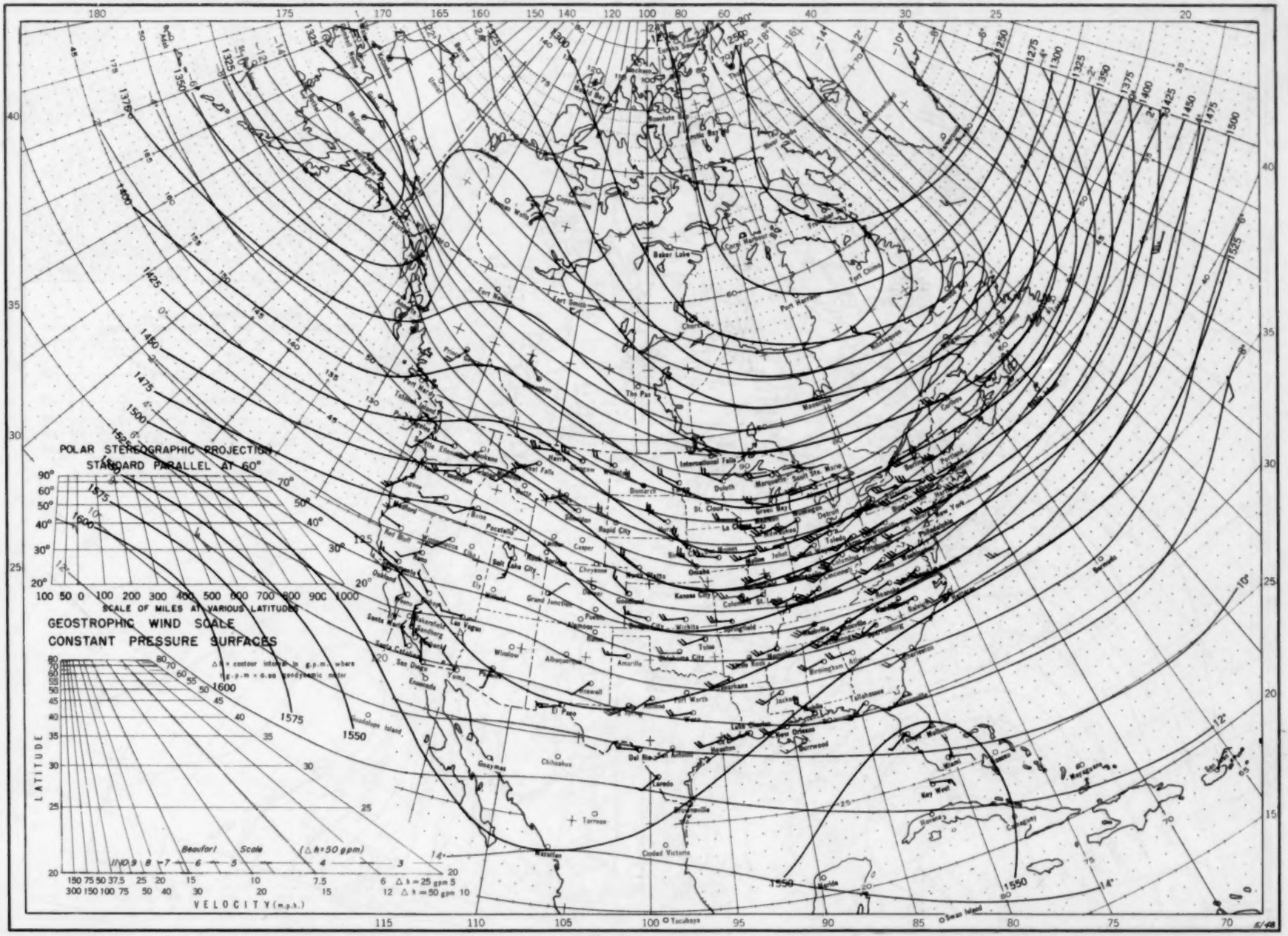
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, January 1951. Inset: Departure of Average Pressure (mb.) from Normal, January 1951.



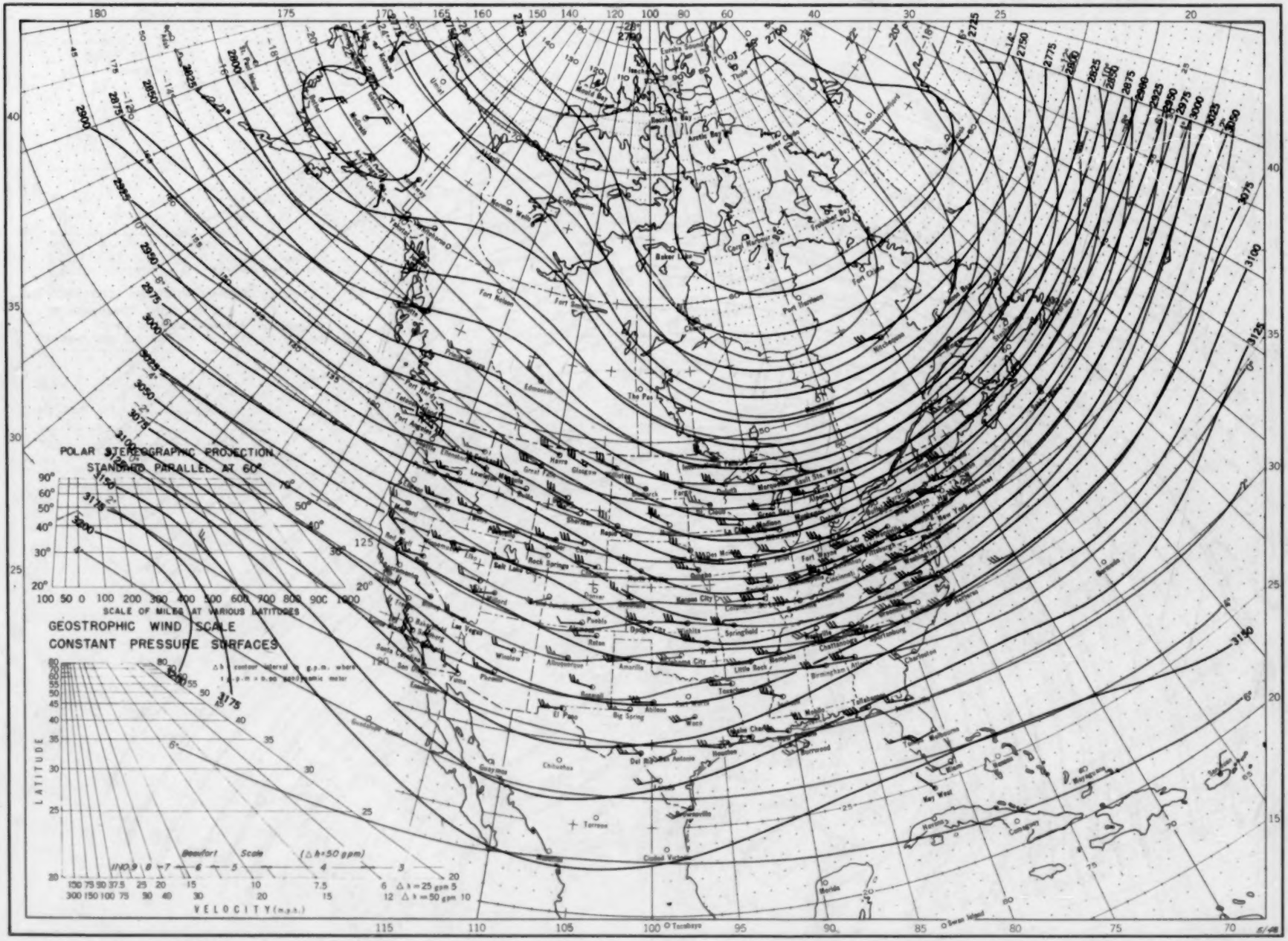
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid from map readings for 20 years of the Historical Weather Maps, 1899–1939.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), January 1951.



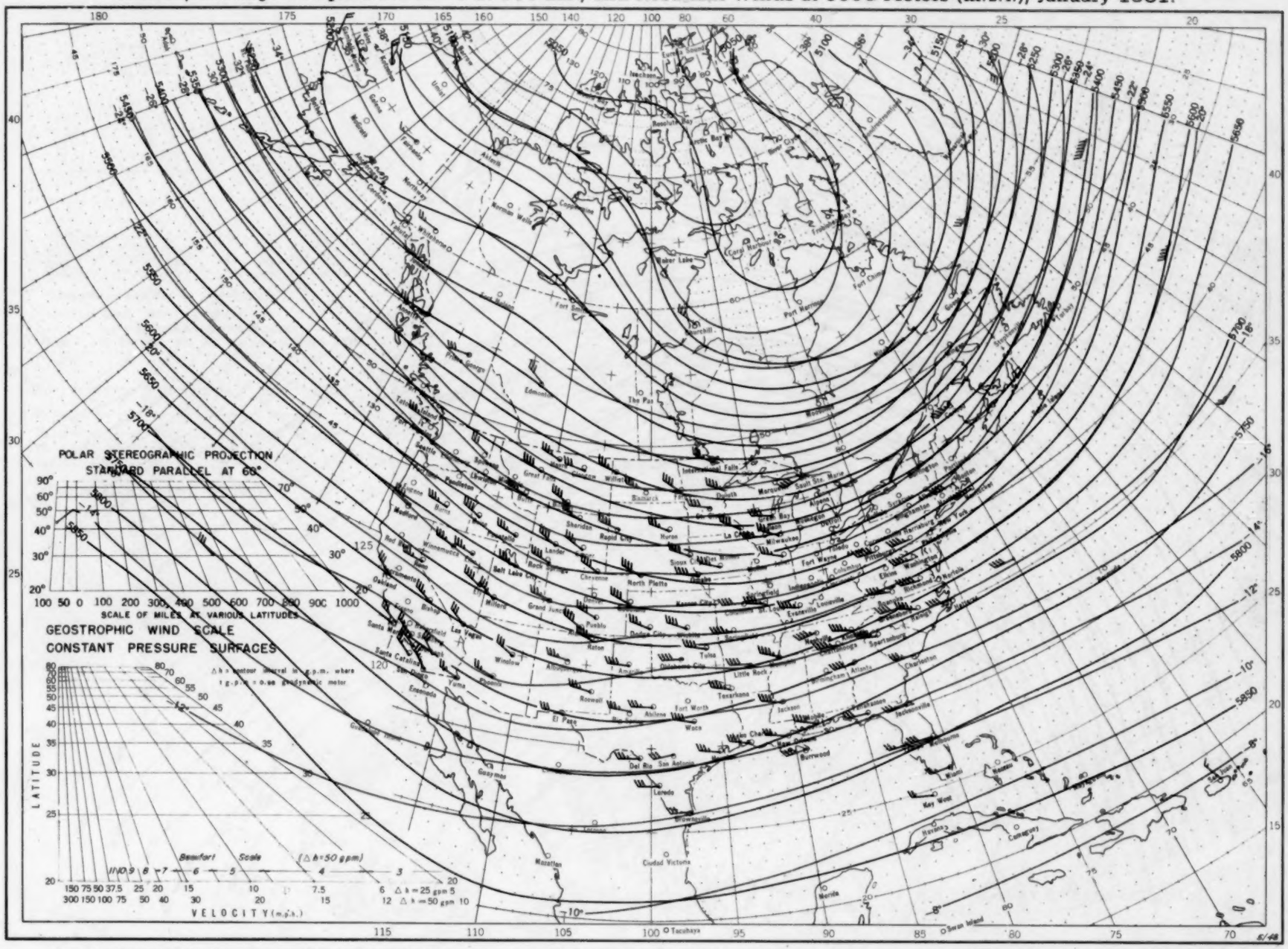
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), January 1951.



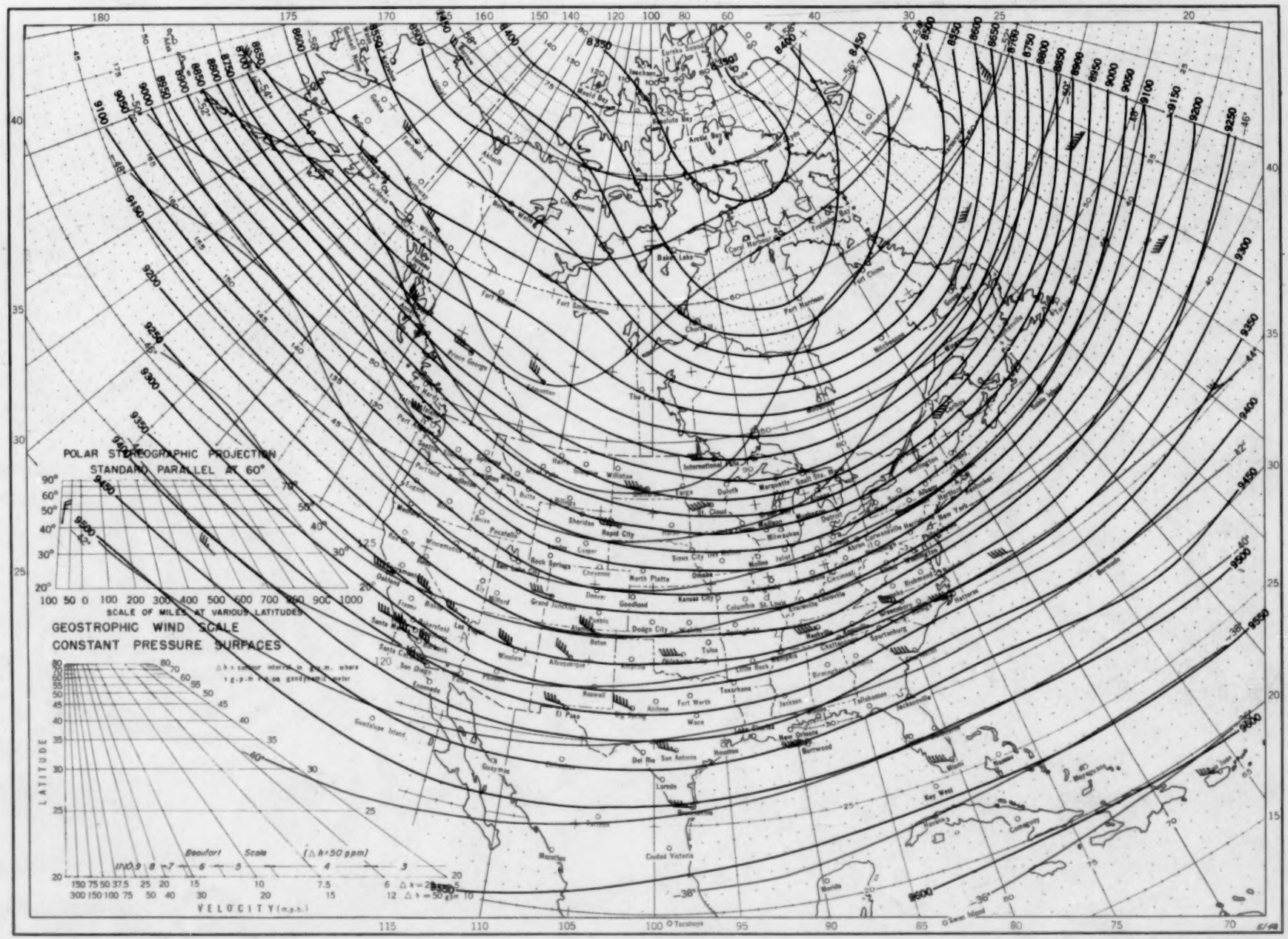
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), January 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), January 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.